VOLUME 104 PART A NUMBER 17 OCTOBER 1957

The Proceedings

OF

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PART A

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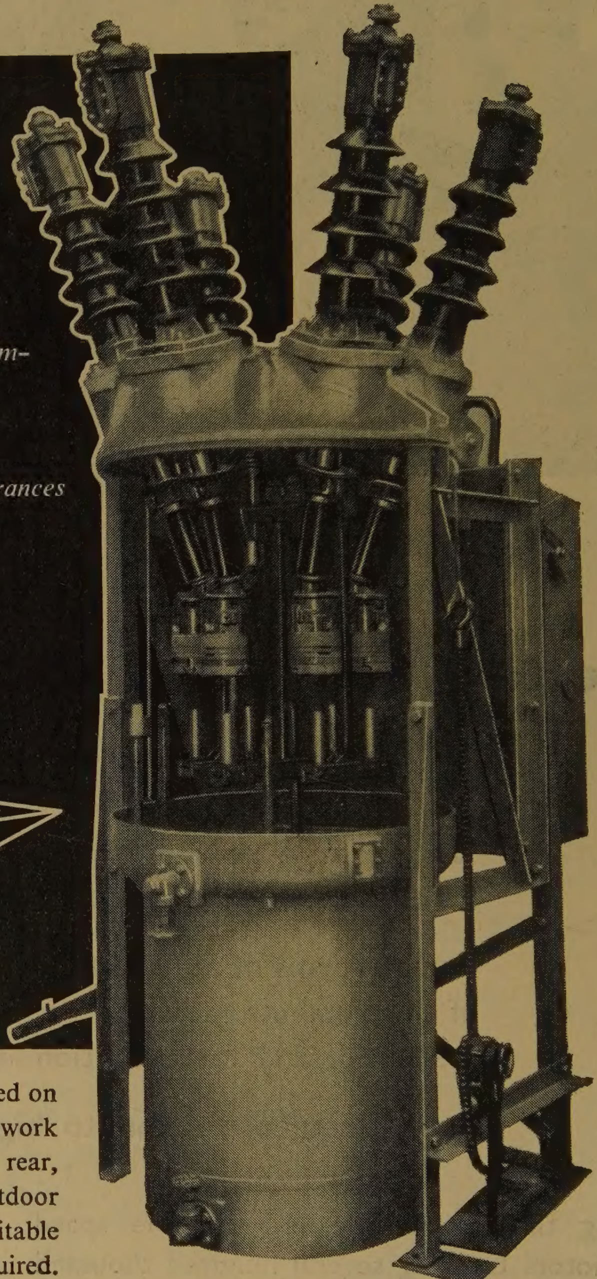

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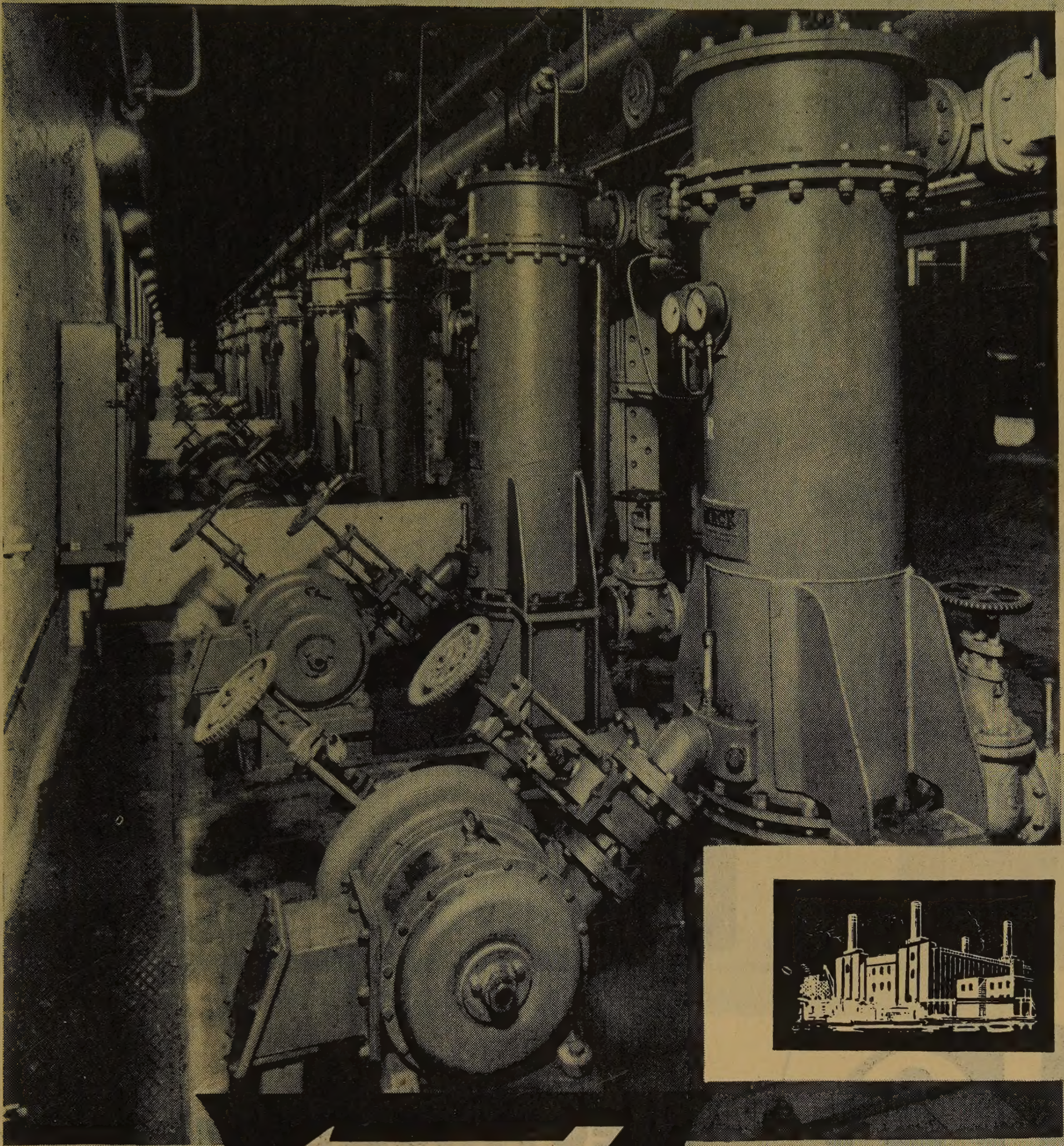

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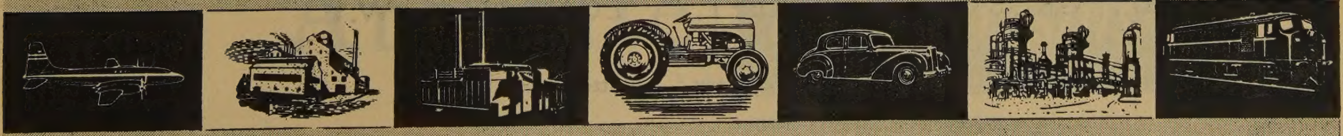

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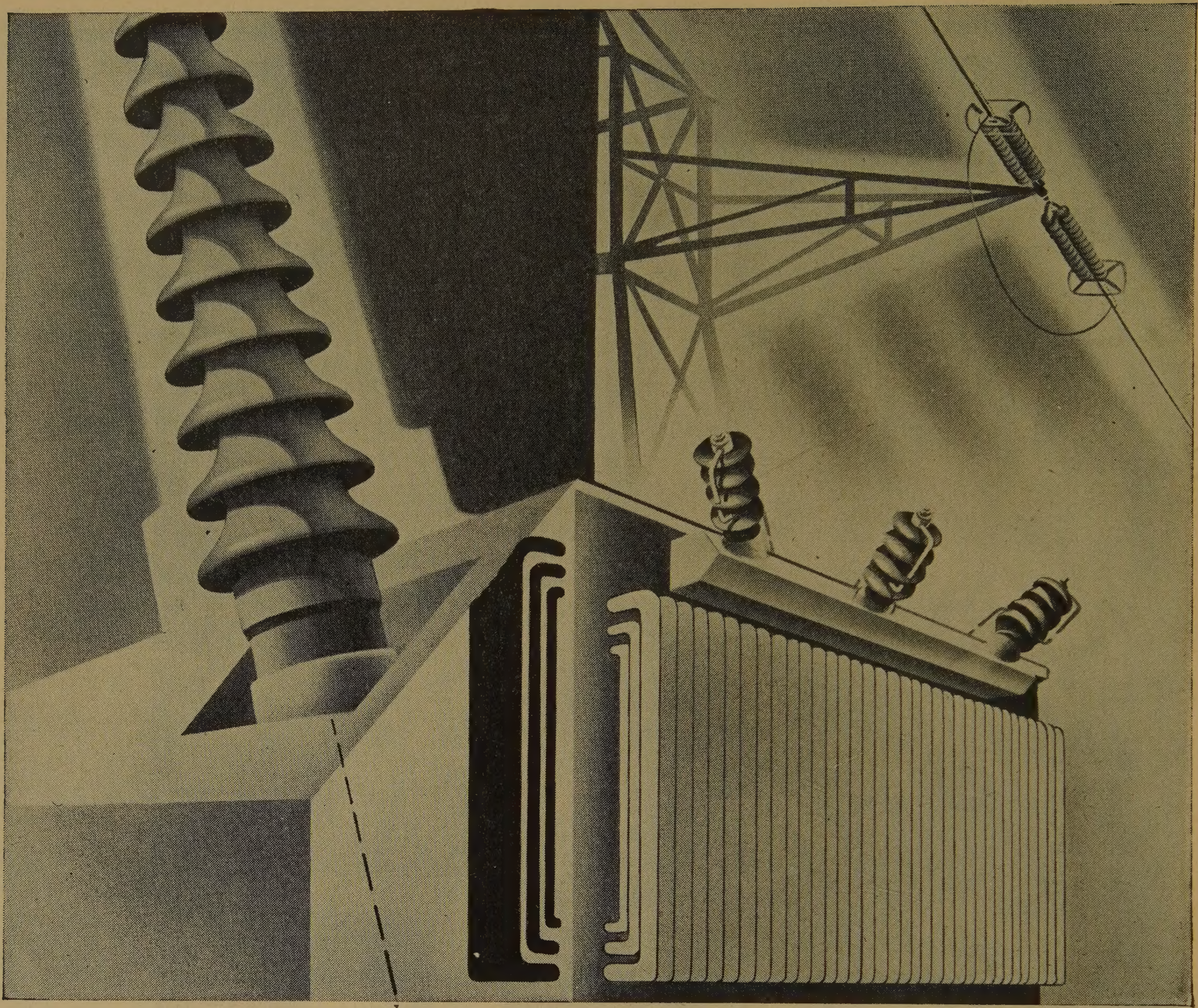

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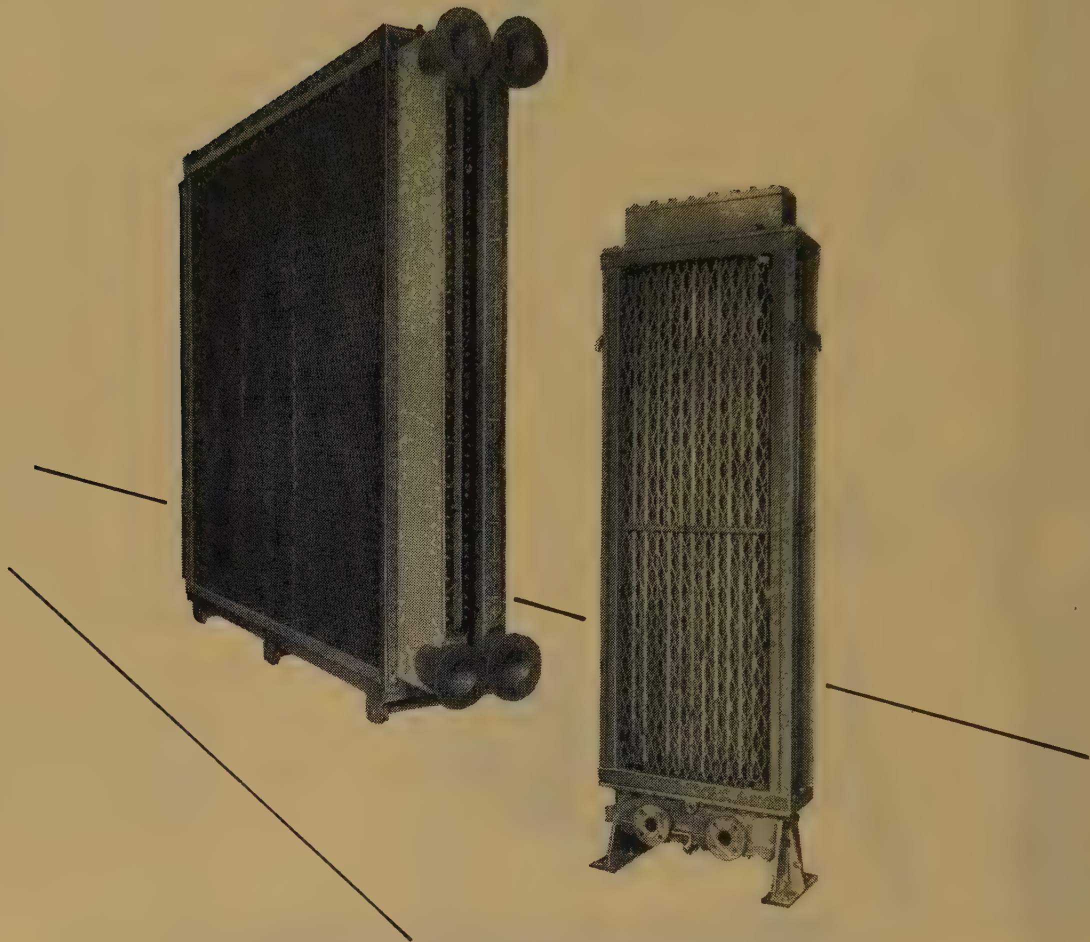

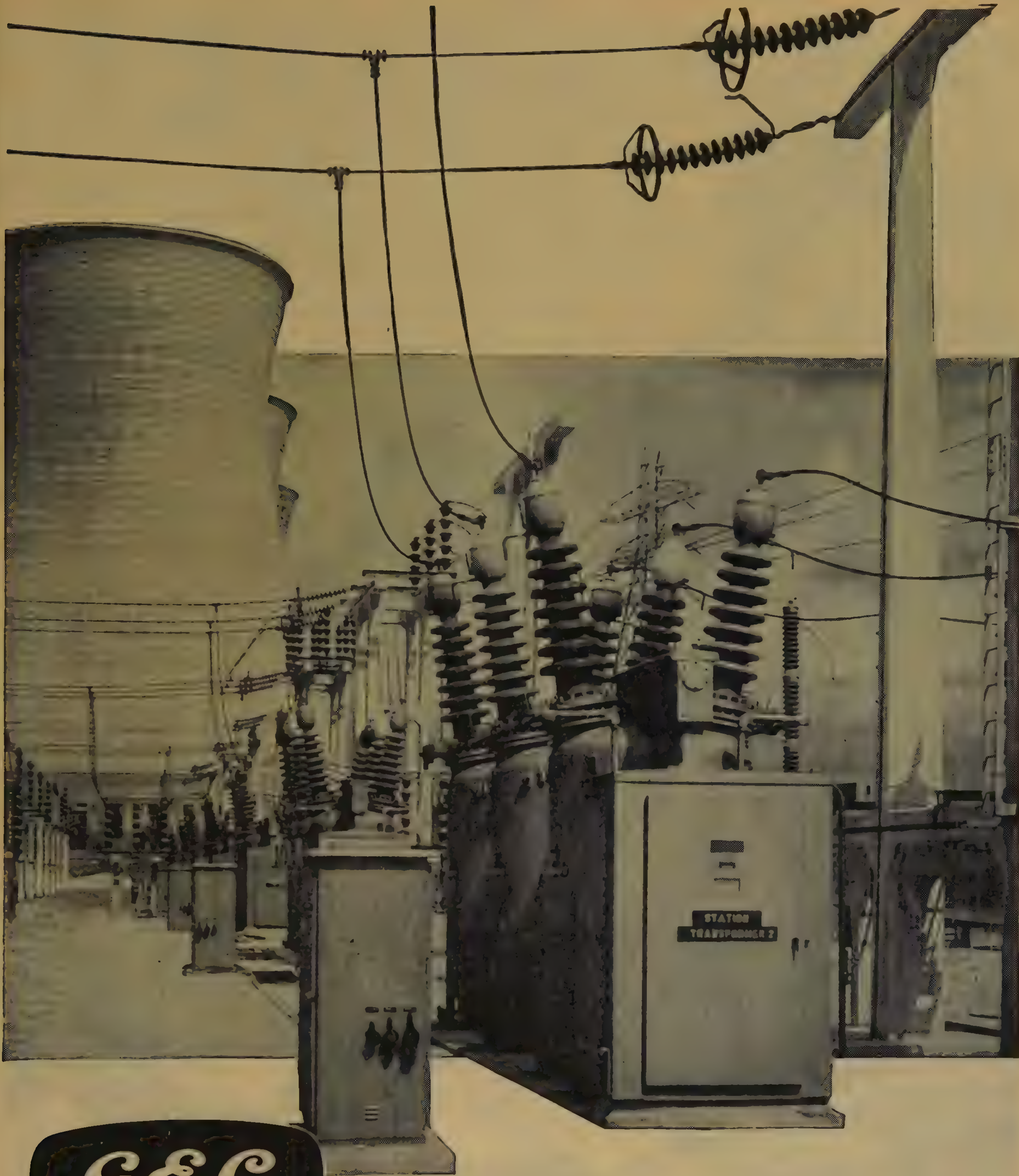

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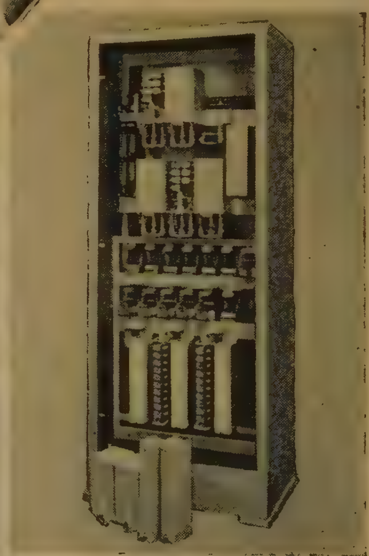

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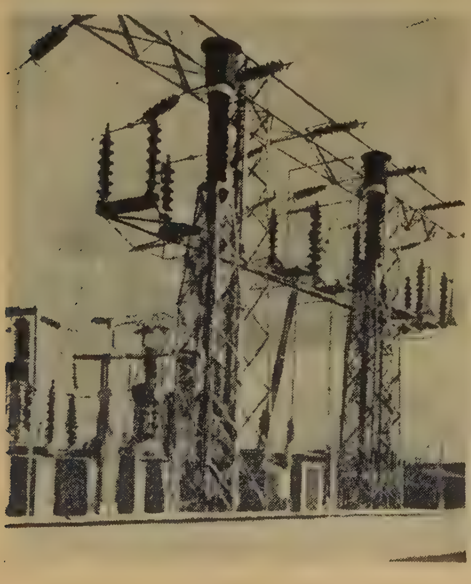

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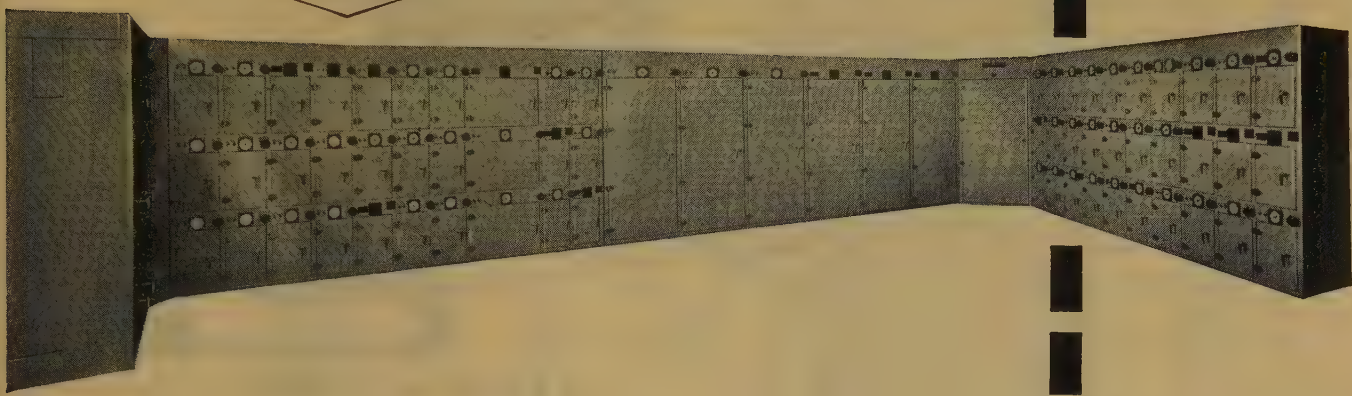
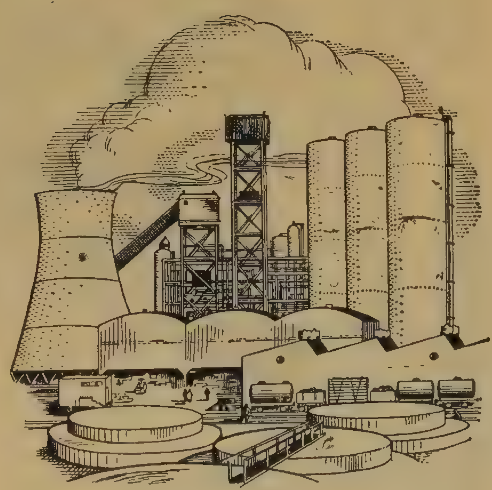


This Dewhurst panel, recently installed in an extensive chemical plant situated in the Midlands, provides positive central control of 75 motors, ranging from $\frac{1}{2}$ to 50 h.p. located in various processing departments of the plant.



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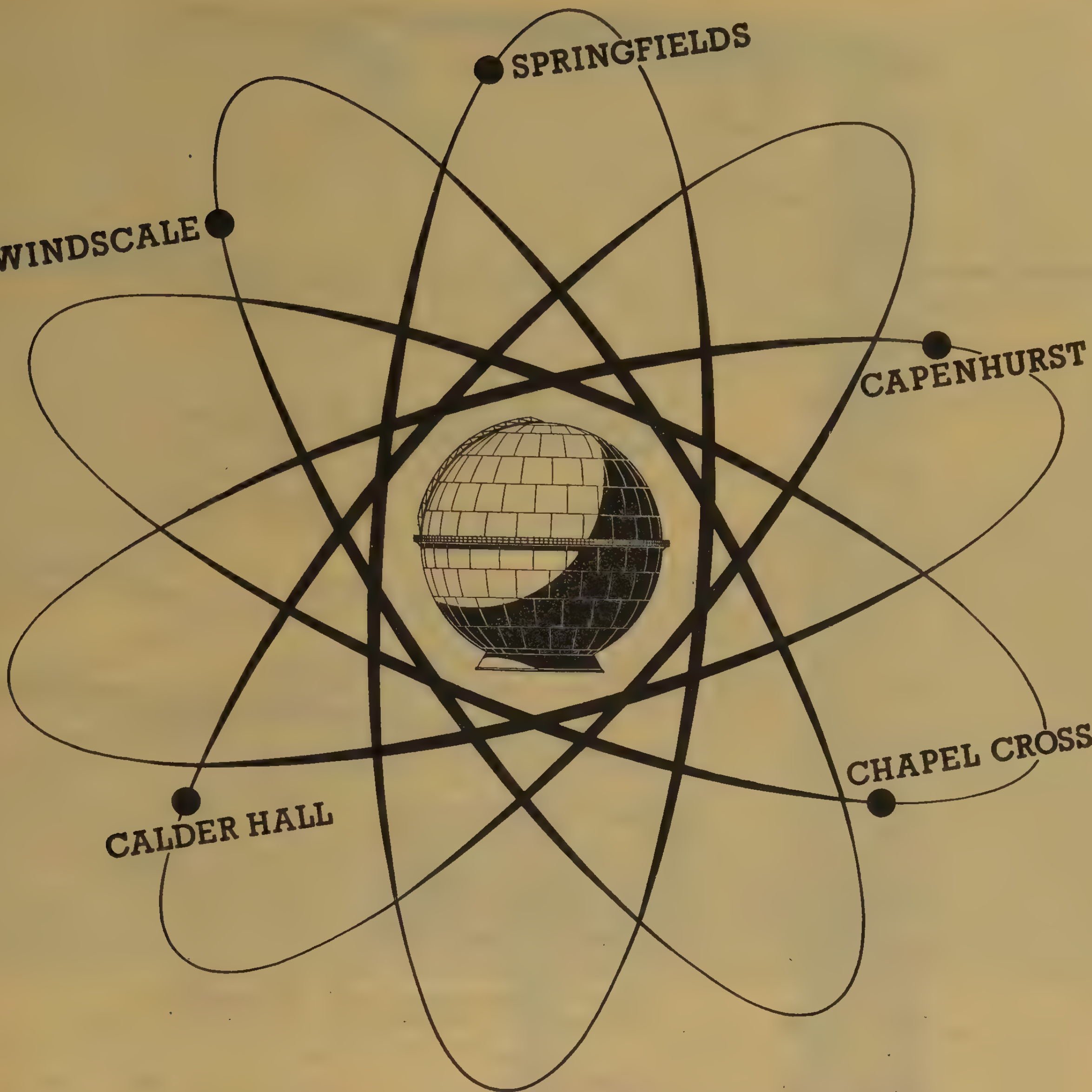

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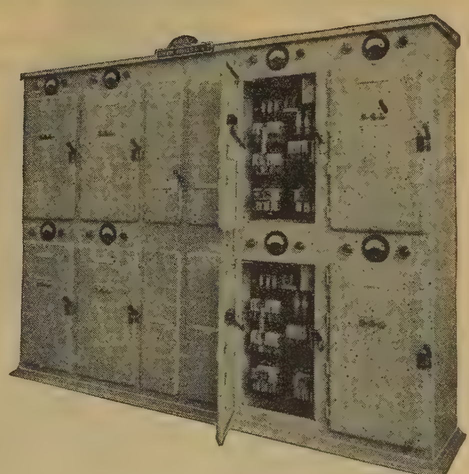

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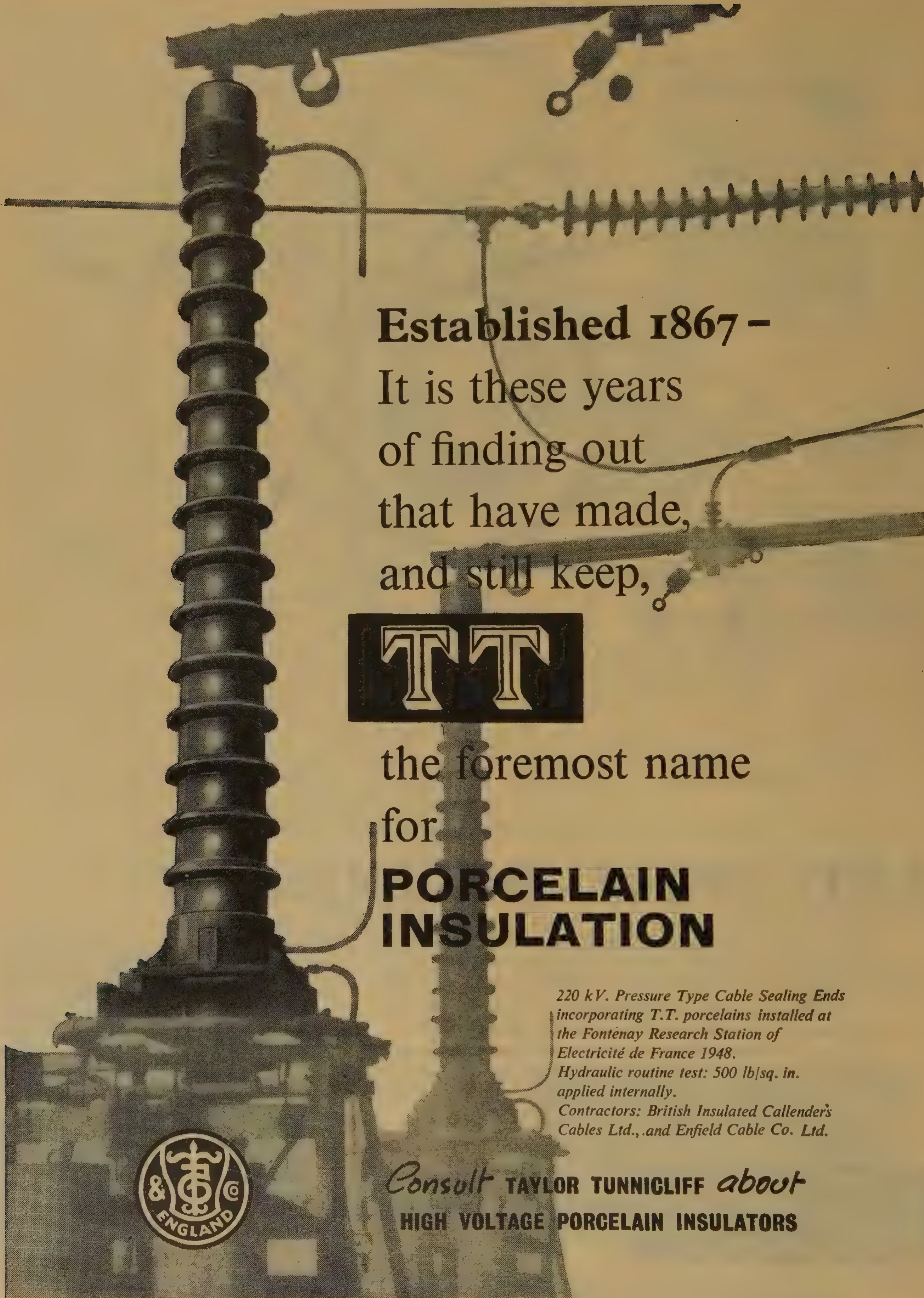
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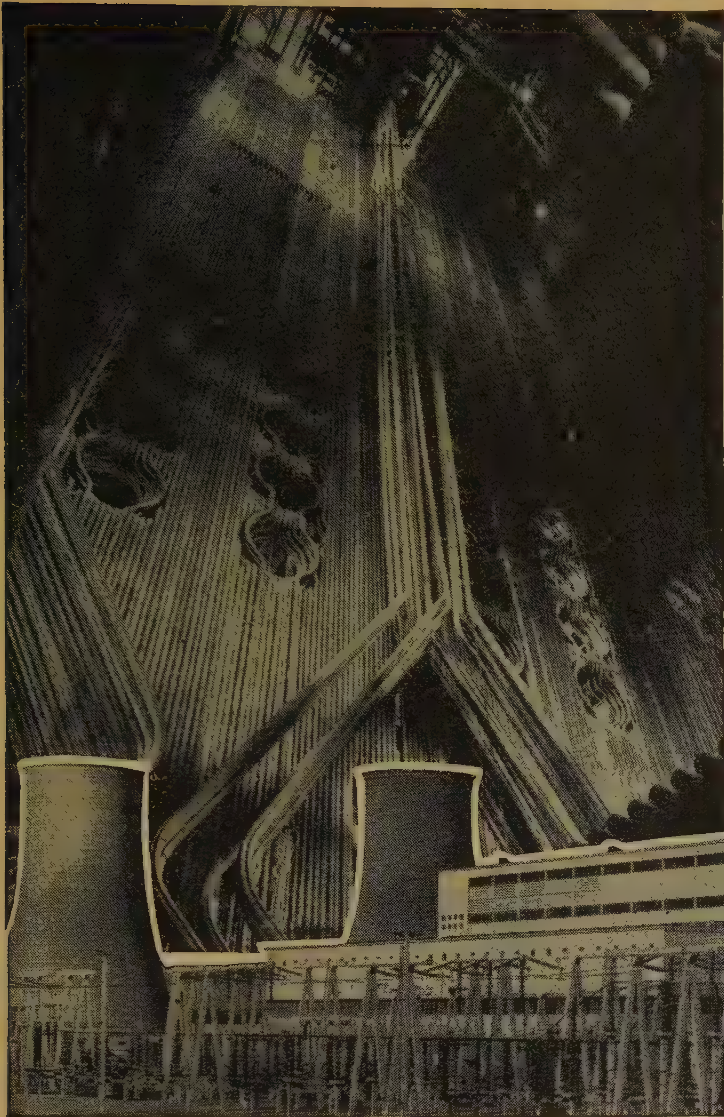
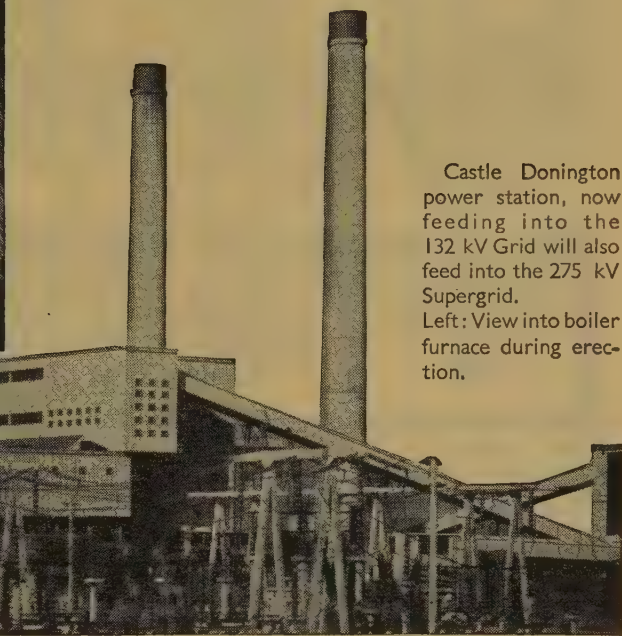


Largest boiler units operating in Europe are BABCOCK



Castle Donington power station, now feeding into the 132 kV Grid will also feed into the 275 kV Supergrid.
Left: View into boiler furnace during erection.

Below: Lifting one of the boiler drums, weighing 90 tons, to a height of 123 feet.

830,000 lb. per hr./100 MW units at Castle Donington

CASTLE Donington (C.E.A., East Midlands Division), is the first power station in Europe with single boiler/turbine units of 100 MW rating and its boilers are the largest in operation in this country.

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The Company has subsequently received orders for boilers of twice this capacity, to steam 200 MW generators, and are engaged in the design of even larger units. Such is the progress of technical development—but always with BABCOCK in the front rank.

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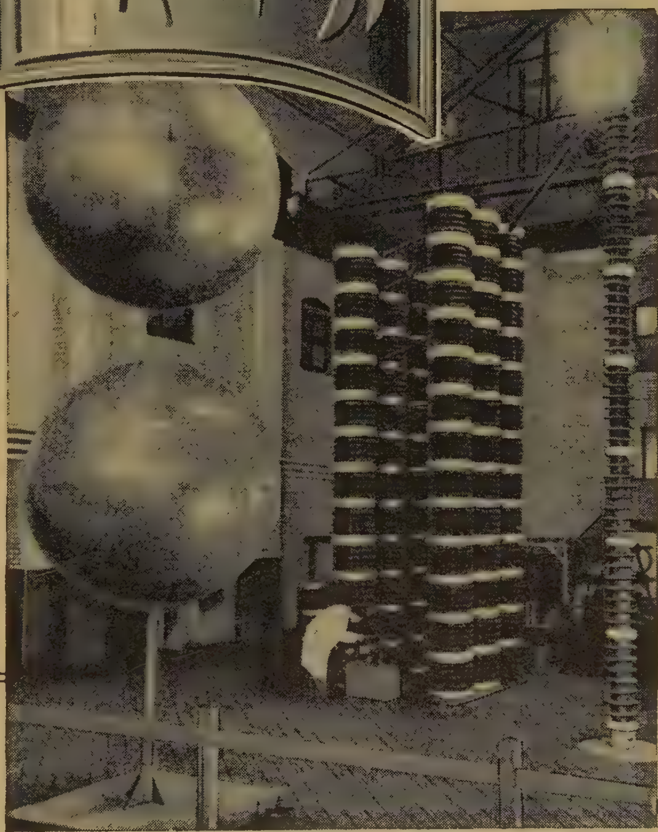

The fourteen members of the Cable Makers Association spent over one million pounds sterling last year on research and development. Part of this great effort is the continual testing—such as is carried out on this surge generator—which is the users' safeguard against technical failures and guarantee that the cables they buy are as reliable and efficient as care and craftsmanship can make them. In its 58 years of existence, the C.M.A. has been associated with virtually every major advance in cable manufacture. It has played a leading part in putting the British cable industry where it is today—at the head of the world's cable exporters.

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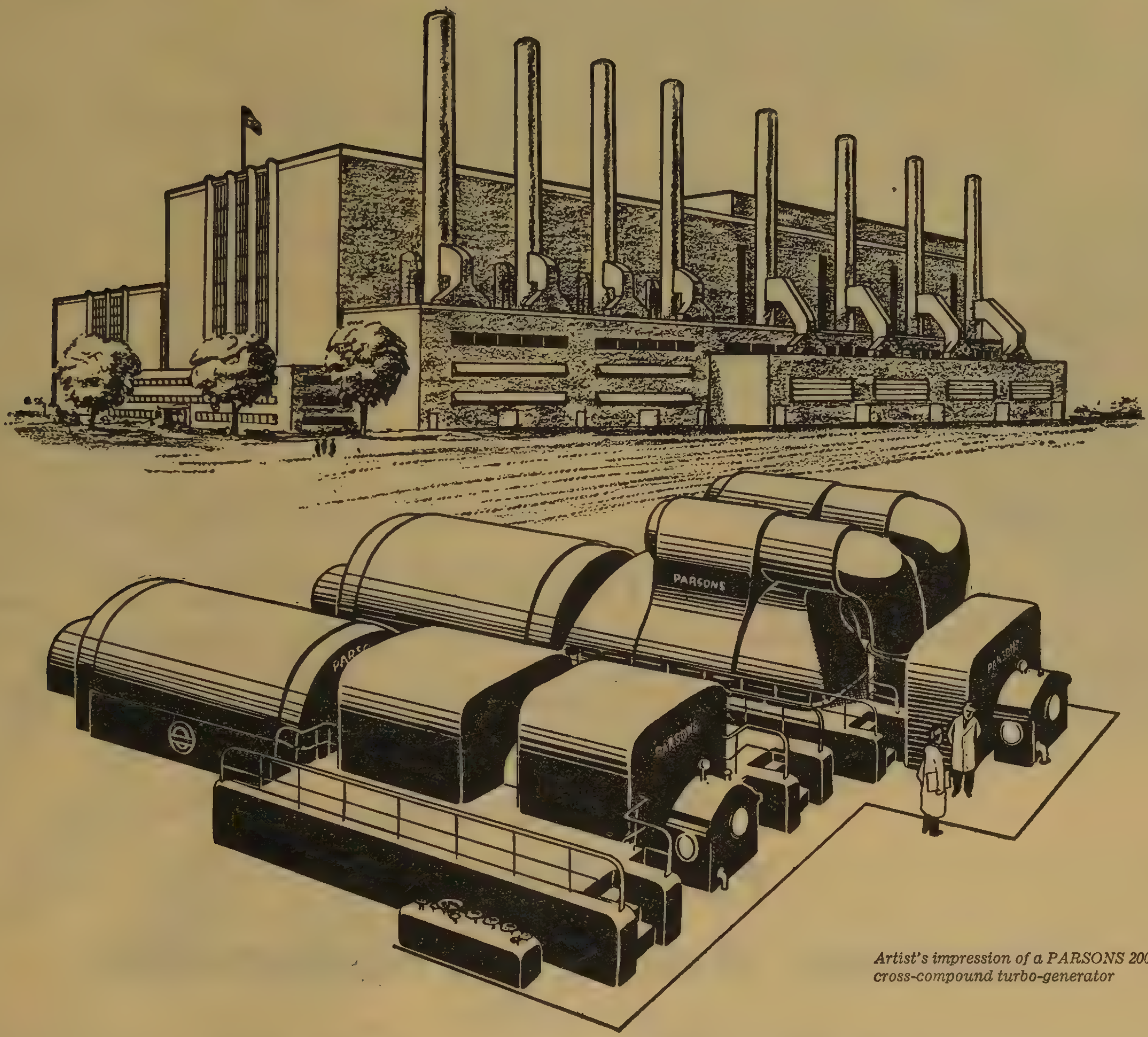

Artist's impression of a PARSONS 200 MW cross-compound turbo-generator

The Hydro Electric Power Commission of Ontario, Richard L. Hearn generating station at Toronto when fully extended will be the largest power station in the world with all turbo-generators from one manufacturer. The first four machines to be installed are Parsons 100 MW type, These are now being implemented by the addition of four 200 MW Parsons cross-compound sets raising the station output to 1,200,000 kW. On these later machines the H.P. lines will run at 3,600 r.p.m., and the L.P. lines at 1,800 r.p.m., a single generator developing 100 MW being coupled to each line . . . Steam conditions, 1,800 lb/ins.^{2} Temperature 1,000° F. Re heat temperature 1,000° F.

PARSONS *turbo-generators*

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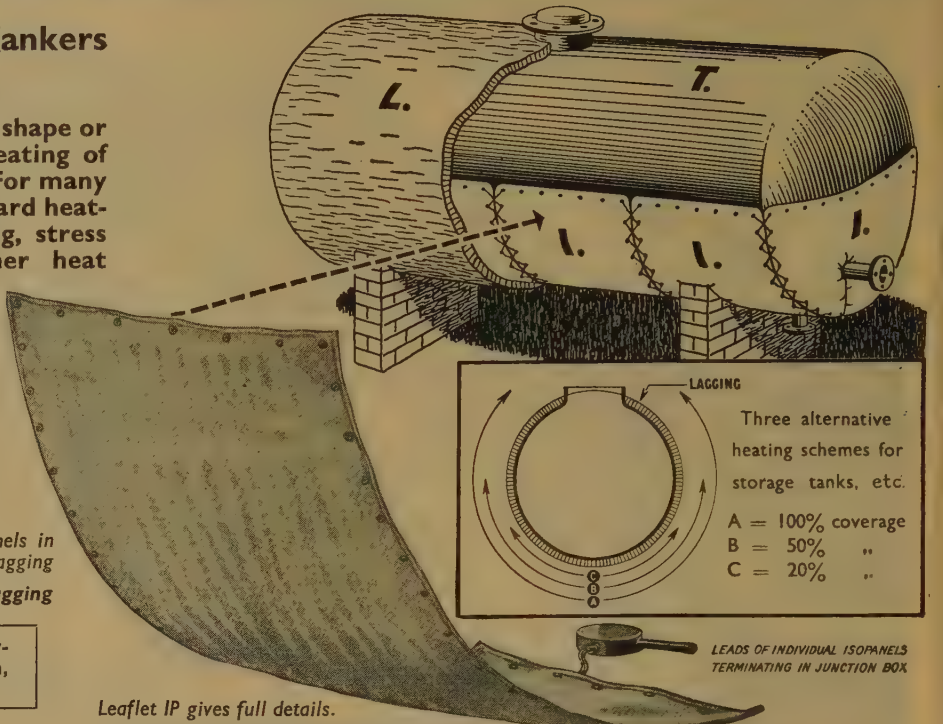

The illustration shows Isopanels in position on storage tank with lagging

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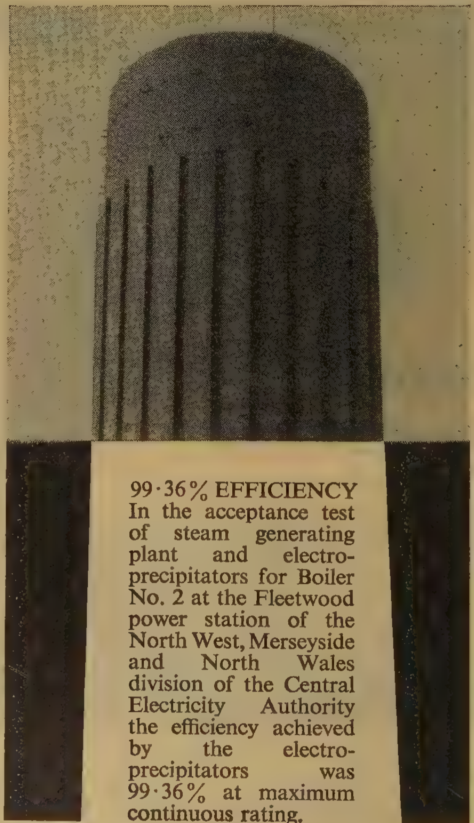
Right–from the start

At the Fleetwood power station of the Central Electricity Authority, where the first boiler was commissioned in May 1955, the first two boilers have each steamed for some ten thousand hours. During this time there has been no sign of any dust build-up on the chimney cap—shown here in unretouched photographs. The total number of hours during which any part of the electro-precipitator has been out on fault is less than 24 and at no time has the complete precipitator been out on fault.

This is a striking testimony that the Simon-Carves electro-precipitators, which extract the flue dust produced by the three boilers at the station, have worked effectively from the time they were first brought into operation.

Because their design is based on long experience of electro-precipitation techniques coupled with up-to-date knowledge of the latest developments, Simon-Carves electro-precipitators are right—from the start.



99·36% EFFICIENCY
In the acceptance test of steam generating plant and electro-precipitators for Boiler No. 2 at the Fleetwood power station of the North West, Merseyside and North Wales division of the Central Electricity Authority the efficiency achieved by the electro-precipitators was 99·36% at maximum continuous rating.

Unretouched telephoto views of the chimney cap at Fleetwood power station, from (left) the north and (above) the south.

***High efficiency electro-precipitation by* Simon-Carves Ltd**
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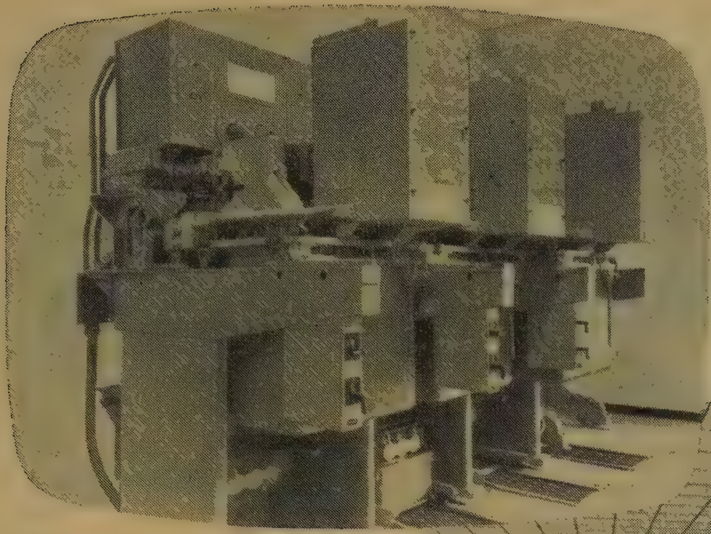
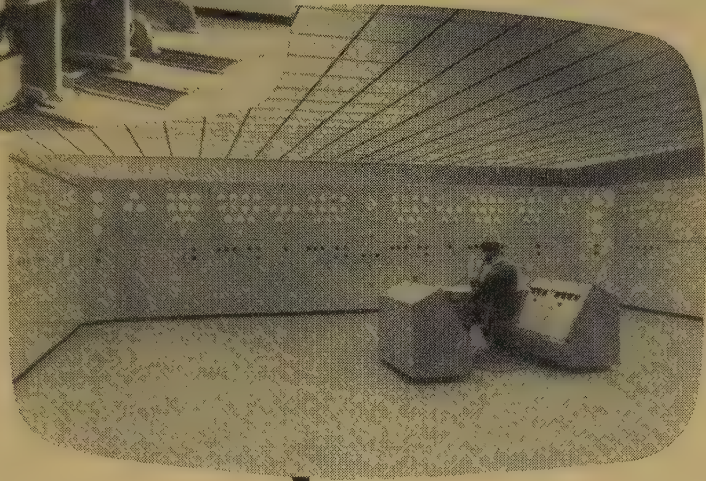
generator switchgear at Calder Hall





Photographs by courtesy of the U.K.A.E.A

The generators at the Calder Hall Power-station of the Atomic Energy Authority are controlled by Reyrolle 11-kV 500-MVA and 750-MVA switchboards and their associated control-boards

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THE PROCEEDINGS OF
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Paper No. 2339 U
Mar. 1957
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ELECTRICAL EQUIPMENT FOR RECTIFIER LOCOMOTIVES

By H. B. CALVERLEY, B.Sc.(Eng.), Associate Member, E. A. K. JARVIS, B.Sc.(Eng.), Associate Member, and E. WILLIAMS, B.Sc.(Eng.), Associate Member.

(*The paper was first received* 16*th October*, 1956, *and in revised form* 23*rd January*, 1957. *It was published in March*, 1957, *and was read before the* UTILIZATION SECTION 14*th March*, *and the* NORTH-WESTERN UTILIZATION GROUP 19*th March*, 1957.)

SUMMARY

The single-phase 50 c/s system of railway electrification has developed extremely rapidly and has been adopted in recent years by France, Turkey, Portugal, the Belgian Congo and Great Britain. Of the many types of locomotive possible, the rectifier type is becoming more and more widely favoured, owing to its combining the best possible traction motor with the lightest form of convertor.

The paper discusses various types of power circuit which have been or could be used on rectifier locomotives, including h.v. and l.v. control systems, types of on-load tap-changing circuit, buck-boost control systems, stepless control systems, bridge and bi-phase rectifier circuits, and methods of connecting motors. Different types of tap-changer, transformer and rectifier are discussed. The operation of the motor on current with ripples is compared with d.c. operation, and the many factors which influence the choice of the ripple current are analysed.

The principal aim of the paper is to bring together the characteristics of transformers, tap-changers, rectifiers and motors, and to discuss the advantages and disadvantages of the various ways in which these items can be put together to form a complete equipment.

No ideal solution is found, as the authors consider that the development potential is too great for any existing equipment to be regarded as final.

LIST OF SYMBOLS

V_{pi} = Peak inverse voltage, i.e. peak anode-cathode voltage.
V_{do} = No-load rectified voltage (mean).
I_d = Direct current (mean) from rectifiers.
V_{so} = No-load r.m.s. transformer secondary voltage.
Note: V_{so} is the anode-neutral voltage in bi-phase.
V_{so} is the total secondary voltage in bridge.
U = Maximum operating speed of locomotive.
T_r = Rated tractive effort of motor.
$u_{r\,max}$ = Highest locomotive speed at rated tractive effort at average line voltage.
d_a = Diameter of motor armature.
l_a = Length of motor armature.

(1) HISTORICAL

The earliest electric traction systems utilized direct-current traction motors, the power being distributed to the trains from the substation generators or convertors also in the form of direct current. With the increasing powers required of locomotives and the electrification of longer main lines, the low-frequency single-phase a.c. system was developed in some countries because it allowed more economic distribution of power to the trains. The use of a low frequency was dictated by the a.c. commutator motor, and the fact that power had to be specially generated for the traction system was not at that time considered to be a drawback. The a.c. traction motor was steadily developed and gave satisfactory service provided that the special low-frequency current was used. For many years the low-frequency a.c. system developed in parallel with the d.c. systems, neither having sufficient economic or technical superiority to oust the other.

The idea of using the modern industrial-frequency alternating current for the distribution of power to the trains found its first application in Hungary in about 1932, and was followed by the Hollenthal experimental line of the German State Railways in 1936 which included rectifier locomotives. There was a break in development during the 1939–1945 War, after which the S.N.C.F. electrified the experimental section Aix-les-Bains–La Roche-sur-Foron in 1950, which included one rectifier locomotive. The Pennsylvania Railroad tried rectifier coaches and locomotives on its 25 c/s system and was soon followed by the New York, New Haven and Hartford Railroad. The S.N.C.F. initiated the large Valenciennes–Thionville 50 c/s electrification using some rectifier locomotives, and 50 c/s schemes were also put in hand in Turkey, the Belgian Congo and Portugal, this last one including rectifier locomotives.

In Great Britain, three multiple-unit trains with rectifier equipments started a regular suburban service on the Lancaster–Morecambe–Heysham line of British Railways in 1953. British Railways announced in March, 1956, their intention to proceed with major electrification schemes using the 50 c/s single-phase system in place of the 1 500 volt d.c. system which had previously been accepted as the standard.

(2) INTRODUCTION

It is not proposed to deal here with the many factors which influence the choice of system or with the merits of each of the

The authors are with the English Electric Co., Ltd.

different types of 50 c/s locomotive. Suffice it to say that of the several types of tractive equipment possible the rectifier type is predominating.

The principal items of a rectifier locomotive equipment are: pantograph, circuit-breaker, transformer, on-load tap-changing equipment, rectifiers, smoothing reactor, and d.c. traction motors.

A transformer is needed on the locomotive to convert the high voltage, usually 25 kV nominal, of the contact wire to a lower voltage for rectification. Usually the transformer is arranged for on-load tap-changing over the complete range from zero output to maximum output voltage, and this tap-changing forms the main method of control of the locomotive power. In some cases d.c. starting resistances have been used to control traction motors supplied from a constant-voltage rectifier, but there is usually a special reason for this type of control which in general is not desirable.

Direct-current series-wound motors, almost identical with those used on d.c. or Diesel-electric locomotives, are normally used; they receive their power from rectifiers connected to give a full-wave output voltage. As the output of these rectifiers contains a large voltage of twice the line frequency, a reactor is connected in the d.c. circuit to limit the resulting ripple current.

Mercury-arc rectifiers of the multi-anode type, the ignitron type and the excitron type have been used. Semi-conductor rectifiers, e.g. germanium and silicon, have considerable possibilities.

The rectifier locomotive owes its superiority to its combining the best type of traction motor with the smallest and lightest type of convertor.

Regenerative braking is technically feasible, using the grid-controlled rectifiers as inverters and separately exciting the traction motors, but has been little used owing to its complicated nature; rheostatic braking is more straightforward. The circumstances in which electric braking is justified are outside the scope of the paper.

Throughout the paper, conventional rectifier-circuit theory is used unless otherwise stated. This theory assumes a d.c. circuit of infinite inductance, so that anode currents are flat-topped.

(3) DESCRIPTION OF POWER CIRCUITS

The problem is to design equipment having maximum performance, maximum reliability, and minimum maintenance, all within the permitted weight and space. This Section will therefore deal with the different circuits which the designer can use and the different parameters he has to settle. It is hoped to show how the solution for any one part of the circuit is influenced by the remainder of the circuit.

(3.1) Traction-Motor Connections and Voltage

(3.1.1) Traction-Motor Fields.

A series-wound traction motor is commonly used in rectifier traction equipments. A separately excited motor would have advantages in some respects, e.g. greater flexibility of field control, smaller reverser switches and field cables, and perhaps better adhesion, but it would introduce certain difficulties. For example, there would be a tendency for commutator flashover when sudden changes of line voltage occurred, the sharing of load between motors connected in parallel would not be so good, and the motor would generate current and feed into faults of certain types.

(3.1.2) Traction Motors in Series, Parallel or Series-Parallel.

If all the traction motors are connected in parallel and controlled by varying the voltage applied to them, as on a rectifier locomotive, it is claimed that the useful coefficient of adhesion is at its highest; for if, under these conditions, one pair of wheels should start to slip, the motor driving them will speed up only a small amount before its current has fallen to the value required to maintain steady slipping. Therefore, no damage is done by the slip, and the wheels regain adhesion when the bad rail condition is passed. During starting of a d.c. locomotive several motors are connected in series and starting resistances are used; the voltage and speed of a slipping motor can under these conditions rise to magnitudes which can result in commutator flashovers and mechanical damage, and also the slip is inherently less likely to stop.

To connect all motors in parallel, however, may have an adverse effect on the size and cost of the equipment as a whole. If the locomotive duty does not demand the highest possible adhesion factor, an important reduction in equipment can sometimes be made by connecting two motors permanently in series [Fig. 1(*a*)]. Compared with four motors in parallel, this circuit

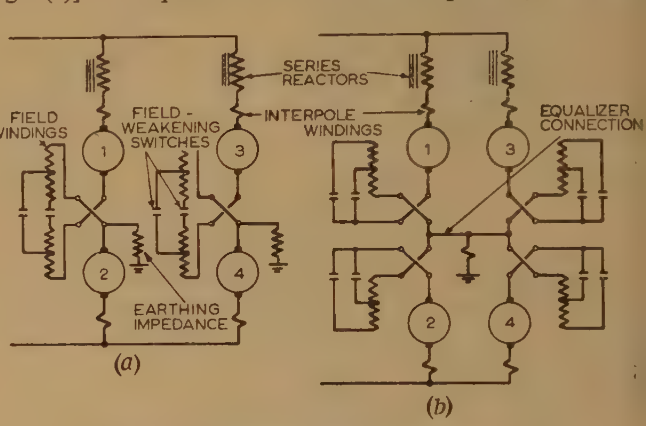


Fig. 1.—Traction-motor connections.
(*a*) Series-parallel. (*b*) With motor equalizer connection.

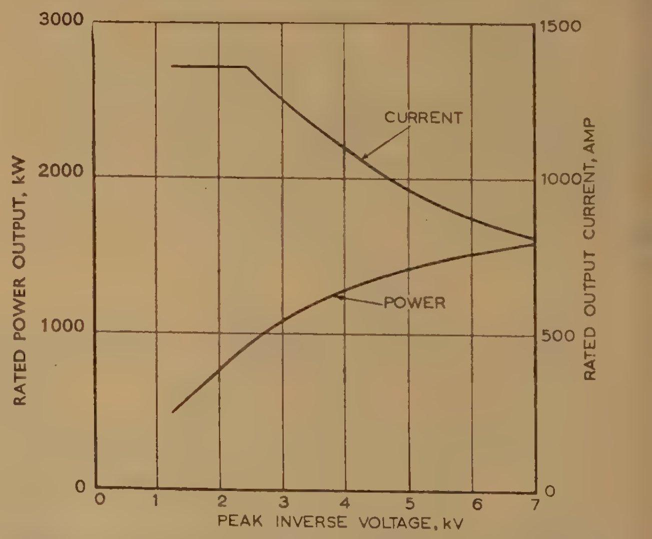


Fig. 2.—Continuous ratings of typical mercury-arc rectifier.

requires rectifiers rated at twice the voltage and half the current and Fig. 2 shows that the rated power output of mercury-arc rectifiers generally increases with voltage. The series connection reduces the total direct current and also the number of reverser contacts and field-weakening switches.

A circuit which gives an intermediate condition, as far as wheel slip is concerned, is shown in Fig. 1(*b*). On commencement of wheel slip, current is transferred through the equalizer

connection, and this tends to reduce the voltage rise on the slipping motor and hence also its increase in speed. The equalizer current provides a simple means of wheel-slip detection and can be used to control the slip.

(3.1.3) Traction-Motor Field Weakening.

It is usual in d.c. locomotive practice to weaken the field at higher speeds in order to obtain better performance at these speeds. This method has also been used on rectifier locomotives, in preference to the alternative method of raising the transformer secondary voltage and so increasing the motor voltage and hence the locomotive speed.

The increased-voltage method really results in an equipment of higher rated horse-power and greater weight, and can thus be justified only if such an increased horse-power rating is really needed.

The field-weakening method is beneficial (*a*) for a mixed-traffic type locomotive, where a given rated horse-power is needed at high speed for express trains (in weak field) and about the same horse-power for slower trains (in full field), and (*b*) where the rated horse-power is sufficient but a higher power output at maximum speed is desired.

Weak field notches are obtained either by reducing the number of turns in the field winding or by using inductive shunts. The use of non-inductive resistance shunts across the whole of the main field winding, as used on Diesel-electric locomotives, is not good practice owing to the danger of motor flashover in case of sudden changes in line voltage.

(3.1.4) Traction-Motor Voltage and Number of Poles.

The motor-armature diameter is determined from consideration of the performance required (see Section 5.1), and the commutator must, for convenience in construction, be a few inches smaller in diameter. A lap-wound armature is normally necessary in order to give the horse-powers required for locomotives. Fig. 3 shows that the maximum h.p. rating can be obtained over

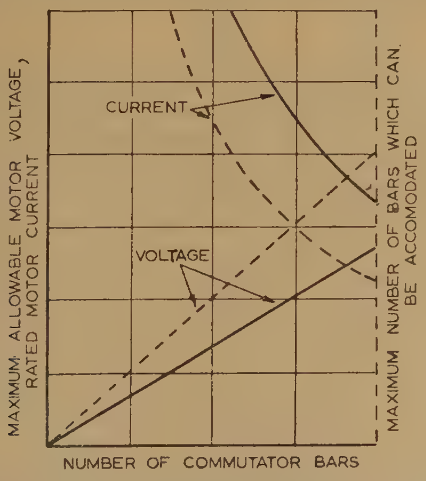


Fig. 3.—Rated current and maximum voltage for a given armature size and different simple lap windings.

——— 6-pole. - - - 4-pole.

a wide range of motor voltage by varying the number of armature conductors and the corresponding number of commutator bars. The upper limit in voltage corresponds to the maximum number of commutator bars which can be accommodated, with the given diameter of commutator, in conjunction with the highest voltage per commutator bar which can be allowed. As the voltage rating increases, the current rating of course decreases in inverse proportion.

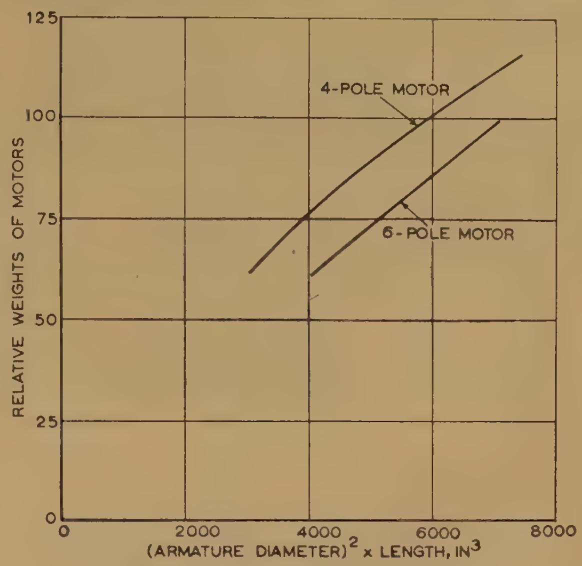


Fig. 4.—Weights of traction motors.

If given a free hand the motor designer would probably choose a 4-pole motor with somewhat less than the maximum number of commutator bars. However, Fig. 4 shows that for a given armature volume the 4-pole motor is heavier than the 6-pole equivalent by between 10 and 20%. In order to reduce axle loads to a minimum it may be necessary to use 6-pole motors, thereby reducing the maximum voltage for which the motor can be rated to about 66% of that for 4-pole motors. The corresponding increase in current rating is a disadvantage for mercury-arc rectifiers, but not for semi-conductor rectifiers, and is a disadvantage also to the control equipment, particularly where the low-voltage type of control is used.

For use with mercury-arc rectifiers the aim is to use motors wound for a minimum rated current, and it is interesting to note that, to a first approximation, this minimum current is independent of motor dimensions, but proportional to the number of poles. The minimum current rating for simple lap windings is of the order of 150 amp per pair of poles for self-ventilated motors and 250 amp per pair of poles for forced-ventilated motors.

The physical size of series reactor in the d.c. circuit is not influenced by the voltage chosen for that circuit.

(3.2) Rectifiers connected in Bridge or Bi-Phase

(3.2.1) Rectifier Inverse Voltage.

The choice of rectifier connection is closely bound up with the choice of voltage in the d.c. circuit, particularly for mercury-arc rectifiers. The power to be delivered at the wheels is put into the motors in terms of the product of voltage and current, the apportioning between them being selected by the locomotive-equipment designer, who must consider the characteristics of the particular motors and rectifiers to be adopted.

Figs. 5(*a*) and 5(*b*) compare the voltages and currents in a bridge and in a bi-phase circuit, for the same power output and peak inverse voltage.

In the bridge circuit, rectifiers 1 and 3 (in series) conduct for one-half of each cycle, and rectifiers 2 and 4 (in series) for the other half of the cycle. Thus at least four rectifiers are required. The peak inverse voltage is

$$V_{pi} = 1\cdot 11 V_{do}\sqrt{2} = 1\cdot 57 V_{do}$$

Therefore $$V_{do} = 0\cdot 64 V_{pi}$$

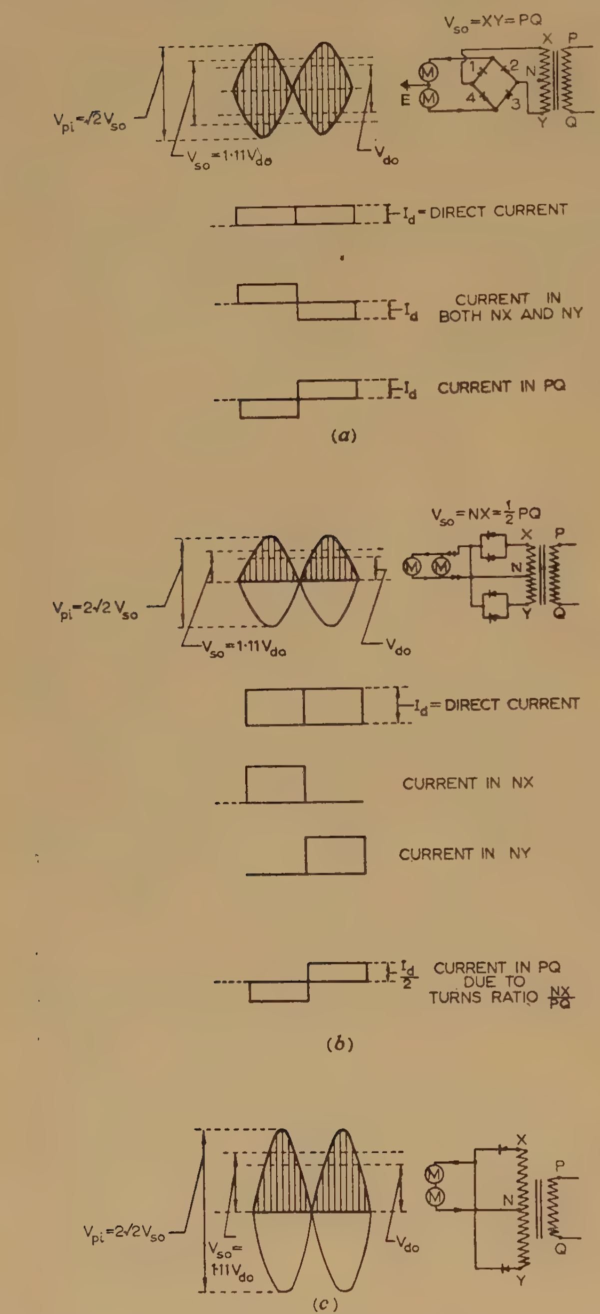


Fig. 5.—Comparisons between bridge and bi-phase connections.

(*a*) Bridge circuit.

'Ideal d.c. output' $= V_{do}I_d \times 10^{-3}$kW
Secondary apparent power $= V_{so}I_d \times 10^{-3}$kVA
Primary apparent power $= V_{so}I_d \times 10^{-3}$kVA
Mean apparent power $= V_{so}I_d \times 10^{-3}$kVA
$= 1{\cdot}11\,V_{do}I_d \times 10^{-3}$kVA $= 1{\cdot}11 \times$ (Ideal d.c. output)

(*b*) Bi-phase circuit for same power output and peak inverse voltage.

'Ideal d.c. output' $= V_{do}I_d \times 10^{-3}$kW
Secondary apparent power
Due to $NX = V_{so}\frac{I_d}{\sqrt{2}} \times 10^{-3}$kVA
Due to $NY = V_{so}\frac{I_d}{\sqrt{2}} \times 10^{-3}$kVA
Total secondary $= 1{\cdot}11\,V_{do} \times \sqrt{2}I_d 10^{-3}$kVA $= 1{\cdot}57 \times$ (Ideal d.c. output)
Primary apparent power $= 2V_{so}\frac{I_d}{2} \times 10^{-3}$kVA
$= 1{\cdot}11\,V_{do}I_d \times 10^{-3}$kVA $= 1{\cdot}11 \times$ (Ideal d.c. output)
Mean apparent power $=$ $1{\cdot}34 \times$ (Ideal d.c. output)

(*c*) Bi-phase circuit for same power and direct voltage as in (*a*) but with double the peak inverse voltage.

In the bi-phase circuit, two rectifiers would suffice to deliver the consecutive half-waves of d.c. voltage. The peak inverse voltage now is given by

$$V_{pi} = 1{\cdot}11 V_{do} 2\sqrt{2} = 3{\cdot}14 V_{do}$$

Therefore $$V_{do} = 0{\cdot}32 V_{pi}$$

With V_{do} thus halved for a bi-phase circuit, the direct current must be doubled, and two rectifiers are shown connected in parallel in Fig. 5(*b*). Consequently four rectifiers are needed just as for the bridge circuit.

Fig. 5(*c*) shows the bi-phase circuit for the same power and direct voltage as in Fig. 5(*a*), but with double the peak inverse voltage. If the current rating were fully maintained at the higher peak inverse voltage of the bi-phase circuit, then only two rectifiers would be needed instead of four. In practice the rated current is reduced, but the rated power per rectifier is appreciably higher owing to using double the peak inverse voltage (see Fig. 2). There will thus be some cases where the required power output can be handled by two rectifiers in bi-phase, whereas four would be required in bridge.

It is helpful at this stage to insert some figures in the formulae to assess the practical meaning of the above comparison. One design of ignitron which has been extensively used is suitable for a peak inverse voltage of about 3 500 volts and can therefore give values of V_{do} of about 1 100 volts connected in bi-phase, or 2 200 volts connected in bridge. Rectifiers have, however, been made which are suitable for about 7 000 volts peak inverse, and hence V_{do} of 2 200 volts connected in bi-phase or 4 400 volts connected in bridge. As the latter voltage is rather high for the motor circuit, it may be advantageous to use the bi-phase circuit to deliver 2 200 volts d.c., requiring 7 000 volts peak inverse and thus obtaining the maximum rated power per rectifier.

For semi-conductor rectifiers, there is no advantage in adopting a bi-phase circuit, because a multiplicity of small rectifiers is involved, and these can be connected in series or parallel as required.

(3.2.2) Transformer Apparent Power.

Irrespective of voltage and of the number of rectifiers chosen, the bridge connection results in a transformer of lower rated mean apparent power for a given d.c. power output. The mean apparent power is calculated from the product of the no-load r.m.s. voltage and the rated r.m.s. current for each winding of the transformer. This has been done in Figs. 5(*a*) and 5(*b*), which show the mean apparent powers to be 1·11 times the d.c. power for bridge, and 1·34 times the 'd.c. power' for bi-phase connection.

The rated mean apparent power of the bi-phase transformer is higher because the secondary winding carries current for only half of the time, i.e. alternate half-cycles. Its form factor, therefore, is bad, which means that the r.m.s. current is high in relation to the mean current.

The weight and volume of a transformer are approximately proportional to the mean apparent power, and the saving due to a bridge transformer can thus readily be assessed.

The term 'd.c. power' referred to above is the product of the rated current and the no-load voltage (V_{do}); it is also known as the 'ideal d.c. output'. The direct voltage available on average at the motors for propulsion is substantially less than V_{do} owing to voltage drops in all parts of the circuit, including the supply system.

(3.2.3) Three-Wire Bridge Circuit.

In Section 3.2.1 the conclusion was reached that, to obtain the full output possible from mercury-arc rectifiers when in a bridge

connection, the direct voltage must be doubled compared with a bi-phase connection—hence the two motors in series shown in Fig. 5(*a*). As already mentioned, however, there is objection to two motors in series, on wheel-slip grounds, but this is overcome if the points E and N of Fig. 5(*a*) are connected together, as in Fig. 8(*b*).

In this 3-wire bridge circuit the motor voltages are as well stabilized as if the motors were connected in parallel, the rectifiers give their full output and the transformer apparent power is minimized.

(3.3) Control of Motor Voltage

All systems of voltage control operate on load; the use of an off-load system would result in an unacceptable loss of tractive effort during a voltage-changing operation. The systems fall into two main groups: tap-changing systems and stepless control systems.

(3.3.1) Tap-Changing.

For all on-load tap-changing schemes, some form of tap-changing impedance is necessary to ensure that a tap-changing operation does not apply a momentary short-circuit across a portion of transformer winding. At least a part of this impedance is introduced into the load circuit during a tap-changing operation; in the case of rectifier equipments, the impedance is introduced into the commutating circuit of the rectifiers. This may result in a momentary drop in output voltage, depending on the scheme in use.

Fig. 6(*a*) shows the sequence for a well-known scheme using a mid-point auto-transformer as the tap-changing impedance. In the running condition shown at (i), the outers of the auto-transformer are connected together; the auto-transformer thus presents negligible impedance to load current, and the output voltage is that corresponding to tap 1. During the transition condition shown at (ii), the impedance of one-half of the auto-transformer is inserted; otherwise the circuit is exactly as for condition (i). A drop in voltage is therefore inevitable in passing from condition (i) to condition (ii). The auto-transformer operates as such in condition (iii), and gives an output voltage corresponding to the mid-point between taps 1 and 2. During the next transition, condition (iv), the impedance of one-half of the auto-transformer is again inserted, but this time it is in circuit with the next higher tap 2. The impedance can have a value such that the overall result is an output voltage not less than that obtained in condition (iii). The next running condition, (v), completes the tap-change.

Fig. 6(*b*) shows an alternative scheme in which all transitions are of the type (iii)–(iv) in Fig. 6(*a*). In running condition (i), the impedance is not in circuit. During transition condition (ii), the impedance is connected between adjacent taps, but the load circuit is unaltered. During condition (iii), the impedance is in circuit with the higher tap; here again, the impedance can have a value such that the overall result is an output voltage not less than that obtained in condition (ii). In condition (iv), the load circuit is connected to tap 2; and transition to (v) does not affect the load circuit, but merely prepares for a further tap-change.

To summarize: a momentary drop in voltage is inevitable with the scheme shown in Fig. 6(*a*), but it can be avoided with the scheme shown in Fig. 6(*b*).

Quite apart from the tap-changing scheme in use, the position of the tap-changer in the locomotive circuit must be decided. Two basic positions are in common use, resulting in the so-called ‘high-voltage’ control and ‘low-voltage’ control.

High-voltage control has been used in Europe, thus following recent practice on some European locomotives with single-phase motors.

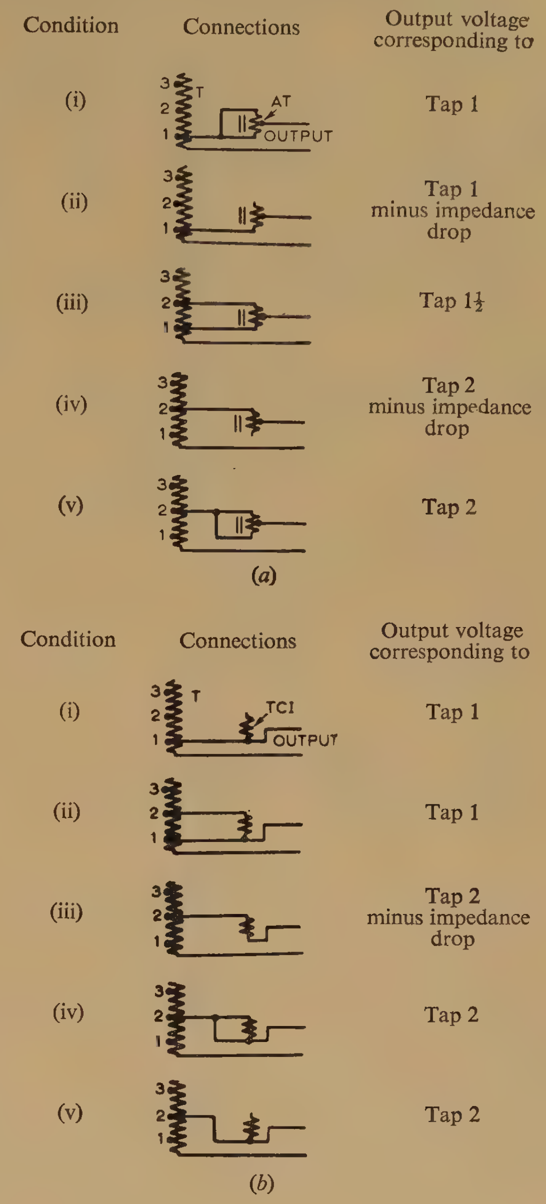


Fig. 6.—Typical tap-changing schemes.

1, 2, 3. Tapping points.
T. Transformer winding.
AT. 2 : 1 auto-transformer.
TCI. Tap-changing impedance.
(*a*) Drop in voltage inevitable.
(*b*) Drop in voltage not inevitable.

Low-voltage control has been used in the United States, where the same method is used on locomotives with single-phase motors. It has also been used on the only three rectifier equipments so far built in Great Britain; these are motor-coach equipments, and are mentioned in the absence of British locomotive equipments.

The approximate duty of the tap-changer for a 25 kV 4 000 h.p. 4-motor locomotive is given in Table 1.

(3.3.1.1) *H.V. Control.*

The main features of h.v. control are shown in Fig. 7. The supply feeds the tapped auto-transformer, and the tap-changer gives a variable-voltage output to the fixed-ratio rectifier transformer.

Table 1

Comparison of Tap-Changer Duties for H.V. and L.V. Control (Motor Rated Voltage of 800 volts)

Type of control	Rectifier connection	Motor connection	No. of motors effectively in series	Tap-changer duty		
				Current rating	Inter-tap voltage	Voltage to earth
				amp	volts	volts
h.v.	Any	Any	1, 2 or 4	200	1 250	25 000
l.v.	Bi-phase	Series Series-parallel Parallel	4 2 1	700 1 400 2 800	250 120 60	5 000 2 500 1 250
	Simple bridge	Series Series-parallel Parallel	4 2 1	1 000 2 000 4 000	250 120 60	5 000 2 500 1 250
	3-wire bridge	Series Series-parallel	2 1	1 000 2 000	250 120	2 500 1 250

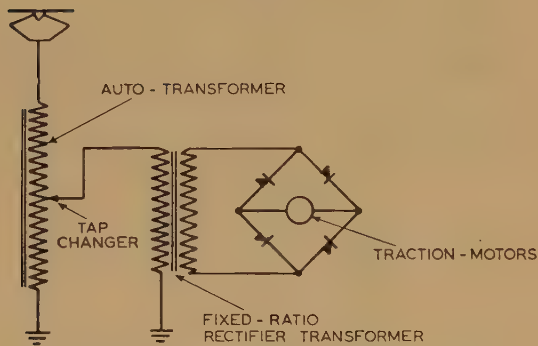


Fig. 7.—Schematic of h.v. control.

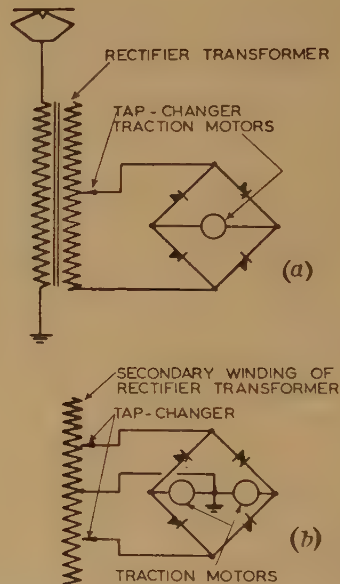


Fig. 8.—Schematic of l.v. control with bridge-connected rectifiers.

(*a*) Simple bridge.
(*b*) 3-wire bridge.

Compared with low-voltage control the advantages of this method include:

(*a*) Easier choice of step voltage, owing to the large number of turns on the tapped auto-transformer.

(*b*) Greater inherent regulation on the lower output voltage tappings. This is partly due to the leakage reactance of the rectifier transformer remaining high, since the number of turns is not reduced. This helps to give smaller inter-notch increases in tractive effort.

(*c*) Switching of smaller currents.

(*d*) The same tap-changer, with the same number of contacts, can be used with different connections of rectifier and motor circuits. This follows from the fact that the tap-changer is ahead of the rectifier transformer.

(3.3.1.2) *L.V. Control.*

The main features of l.v. control are shown in Figs. 8 and 9. The supply feeds the primary winding of the rectifier transformer, which is provided with a tapped secondary winding. The tap-changer applies variable voltage to the rectifiers. The duty of the tap-changer depends on the type of rectifier connection and motor connection in use; approximate figures for the 4 000 h.p. equipment mentioned above are given in Table 1.

The number of contacts required on the tap changer depends on the rectifier connection in use; and the bi-phase connection requires approximately twice as many as the simple bridge connection. With the 3-wire bridge circuit, tap-changing can be carried out alternately on the two halves of the secondary winding; this requires the same number of contacts as the simple bridge circuit.

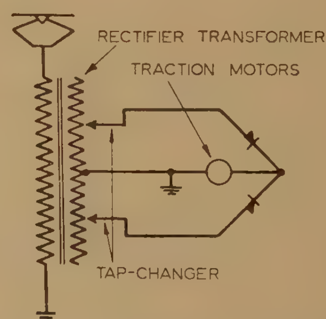


Fig. 9.—Schematic of l.v. control with bi-phase-connected rectifier

Compared with h.v. tap-changing, the advantages of this method include:

(*a*) Lowest possible transformer size. This is especially marked when dual-voltage working is required, and is dealt with in the Section 3.3.1.3.
(*b*) Lowest possible transformer losses and smallest radiator.*
(*c*) Better power factor.*
(*d*) Selector contacts are more readily accessible.

(3.3.1.3) *Transformer Rating.*

The method of tap-changing has an important bearing on the transformer rating required; other factors are the type of rectifier connection, and whether or not dual-voltage operation is required. In the case of h.v. tap-changing, a further factor is the maximum voltage to earth for which the tap-changer is suitable; this determines the voltage of the top tapping on the auto-transformer.

The ratio of total winding rating to ideal d.c. output may be used as a guide to the total size of transformer (or transformers) necessary. 'Ideal d.c. output' is the output which would be obtained if the equipment had zero reactance and no losses. Fig. 10 shows how the ratio depends on top tap voltage when

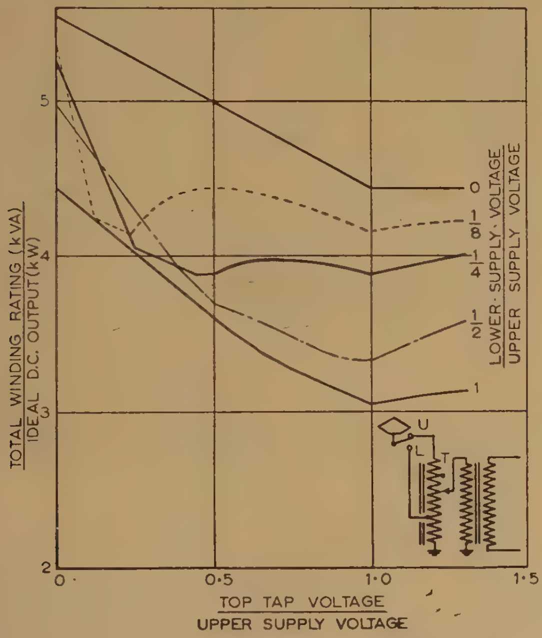


Fig. 10.—Total rating of transformer windings for dual-voltage equipments with h.v. control.

Curve 1 represents single-voltage equipments.
L. Connection for lower supply voltage.
U. Connection for higher supply voltage.
T. Top tap.

Curves are based on: bridge-connected rectifiers; 'square-wave' theory, no overlap; perfect grading of winding cross-sectional areas.

h.v. tap-changing is used; the various curves are for different ratios of the two supply voltages at which dual-voltage operation is obtained by the method shown. In constructing the curves, perfect grading of the cross-sectional areas of the winding has been assumed; since such perfect grading is unlikely to be achieved, the curves show least values which will usually be exceeded in practice.

The total winding ratings necessary for l.v. tap changing are shown in Fig. 11, and three methods of obtaining dual-voltage operation are indicated. Method (*c*)—series-parallel primary—is practicable only when the ratio of the two supply voltages is a simple fraction ($\frac{1}{2}$, $\frac{1}{3}$, etc.); the graph for this method is therefore shown as isolated points joined by a dotted line.

* Refer to Fig. F on page 374.

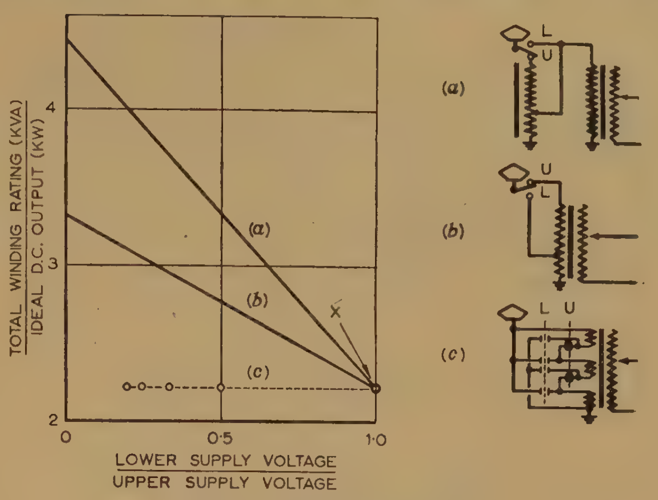


Fig. 11.—Total rating of transformer windings for dual-voltage equipments with l.v. control.

X. Single-voltage equipment.
L. Connections for lower supply voltage.
U. Connections for higher supply voltage.

Curves are based on: bridge-connected rectifiers; 'square-wave' theory, no overlap.

(*a*) By auto-transformer.
(*b*) By tap on primary.
(*c*) By series-parallel primary.

The curves are based on bridge connection of the rectifiers; the use of a bi-phase connection would in every case increase the ratio of total winding rating to ideal d.c. output by 0·46.

(3.3.1.4) *Tap-Changing Impedance.*

The tap-changing impedance may be resistive or reactive, the ohmic value being determined mainly by the permissible inter-notch jumps in tractive effort during the starting sequence. To cause the same effect on the motor circuit a lower impedance is needed if resistive than if reactive, in the ratio of approximately 1 : 3 for a bi-phase circuit and 2 : 3 for a bridge circuit. The circulating current drawn by the impedance whilst connected across adjacent transformer tappings is therefore larger if a resistor is used than if a reactor is used.

Since the tap-changer contacts handle this circulating current in addition to the current due to the load, the choice of resistor or reactor is partly governed by the performance of the tap-changer. A resistor is normally used for h.v. tap-changing and a reactor for l.v. tap-changing.

(3.3.1.5) *Special Circuits to reduce Tap-Changing Equipment.*

With l.v. control, a mid-point auto-transformer is commonly used as the tap-changing impedance, since it enables the number of output voltages to be double the number of tappings, whilst introducing only very small losses. The mid-notches are always correctly spaced, irrespective of line voltage or load. On the mid-notches [Fig. 6(*a*) condition (iii)] the magnetizing current drawn by the auto-transformer affects the power factor adversely.

An alternative method of obtaining additional notches is to use the tap-changing impedance, in circuit with the next higher voltage tapping, as a pseudo-mid-notch [Fig. 6(*b*) condition (iii)]. The impedance is designed for notching at a given line voltage and load current, and is not the correct value for other conditions. If the tap-changing impedance is a resistor (e.g. for h.v. control), the losses on the pseudo-mid-notches affect the efficiency adversely.

Buck and boost schemes have also been used, with the object of reducing the number of tapping contacts by using them twice during the accelerating period. Examples of two of the circuits

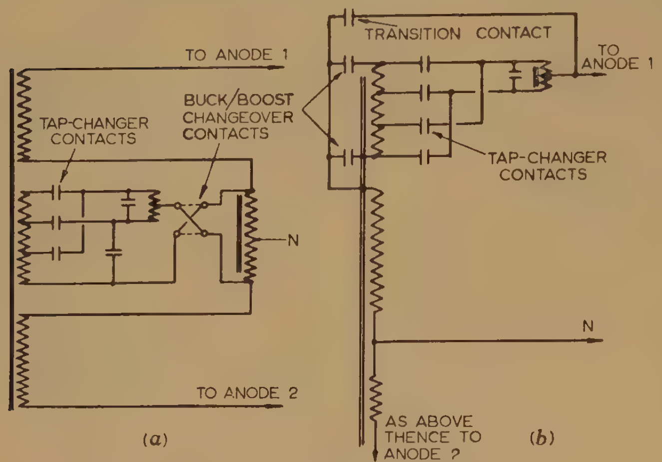


Fig. 12.—Buck-boost schemes.

(a) With auxiliary transformer.
(b) Without auxiliary transformer.

are shown in Fig. 12. Some of these schemes add a transformer to the circuit, so increasing the total weight, but others do not.

On constructing the notching curves for a rectifier equipment, it is found that in the region of low direct voltages the number of notches, and therefore the number of tap-changer contacts, tends to become too large for convenience. This is mainly due to the traction-motor speed/current characteristic becoming flatter as the direct voltage is reduced. It is accentuated by the lessening of the voltage regulation of the rectifier equipment, expressed as change in voltage with respect to current, as the direct voltage is reduced by tap-changing.

It is therefore beneficial to increase the rectifier-equipment voltage regulation, and this can be done in several ways. Firstly, the transformer should be designed for maximum reactance on the low tappings. If this is not sufficient, additional reactors can be incorporated in the rectifier commutating circuit; these reactors should be removed from circuit on the higher notches, where they are not necessary, since they adversely affect the performance and power factor.

Another way in which steeper characteristics have been obtained is by the use of a limited amount of resistance in the traction-motor circuit. Here, again, the resistance is cut out of circuit before any normal running speed is attained.

(3.3.2) **Stepless Control.**

Stepless control results in virtually stepless variation of the voltage applied to the motors. It eliminates notching peaks, and consequently allows a higher starting tractive effort for a given adhesive weight, and gives smooth starting. Little has been done in this way on rectifier vehicles, but the possibilities are considerable.

Two basic methods are possible—the use of induction regulators or regulating transformers, and the use of firing delay on mercury-arc rectifiers.

(3.3.2.1) *Regulators or Regulating Transformers.*

Transformers in which a contact rolls over the periphery of the secondary winding were built in 1939 for two motor-coaches of the Swiss Federal Railways. The coaches were fitted with $16\frac{2}{3}$ c/s traction motors. This type of transformer gives truly stepless control, but no further work seems to have been done on this scheme.

The use of induction regulators is a possibility which does not seem to have been tried. No doubt this is due to the large size of such a regulator, the expensive construction, and the considerable torque required to operate it or to hold it in any position.

Regulating transformers of the type in which contacts slide or roll across the windings could be used, the driving torque now being small.

With induction regulators or regulating transformers, it is desirable to reduce their rating (apparent power) and size by using them to span the voltage between tappings on the main transformer.

(3.3.2.2) *Rectifier Firing Delay.*

A very useful and important property of the mercury-arc rectifier is that its output voltage can be controlled by varying the phase of the grid or ignitor impulse relative to the anode voltage wave. This type of control, if correctly applied, would provide considerable advantages in reducing equipment weight and improving performance.

One method of applying grid control would be to use phase-angle control with anode voltages of about 20% or 30% of their maximum value. When starting a train the rectified voltage would be increased steadily by phase-angle control till it reached the value corresponding to no firing delay. After this the increase in voltage would continue by normal on-load tap-changing, without firing delay.

By the use of such a method of control, an infinitely smooth increase in tractive effort would be obtained at standstill, and sudden jumps in tractive effort at the break-away point would be avoided.

The usual reasons for avoiding the use of grid control, such as worsening of power factor and increase in harmonics, are of little account with this scheme because the power being drawn from the line is small at starting, and, moreover, on any normal running notch the grid control is removed.

(4) DESCRIPTION AND OPERATION OF APPARATUS

(4.1) The Transformer

The transformer is the heaviest single item of equipment in the locomotive, and it is therefore worth giving every consideration to means of attaining the minimum possible weight.

(4.1.1) **Insulation and Cooling.**

For voltages up to about 15 kV it is practicable to use air as the insulating and cooling medium, and this promotes lightness and a low fire risk. For higher voltages the greater electrical clearance and creepage distances needed would cause an air-insulated transformer to be excessive in size. For 25 kV systems, therefore, it is normal to use a liquid as the insulating medium.

In order to achieve the desired low weight it is customary to use a current density several times greater than would be normal for a conventional substation transformer. This results in correspondingly high copper losses which must be accepted as the penalty to be paid for lightness and smallness. The high losses could not be dissipated by natural cooling, and forced oil circulation is therefore adopted in order to circulate the oil between the transformer and a separate radiator and to obtain better heat-transfer factors.

The high losses must be transferred from the hot copper to the oil in spite of the limited surface area for heat transfer; hence for a given copper temperature the hot-oil temperature must be kept relatively low. The heat must then be transferred to the air, and it is apparent that a large radiator is required because of the low temperature of the hot oil.

Thus a small light transformer (high losses) will possibly necessitate additional locomotive weight owing to the space occupied by the large radiator. The best compromise between transformer size and radiator size is a design problem.

(4.1.2) Cores.

The core is built up from laminations of grain-oriented silicon-iron alloy, which can be operated at flux densities near to saturation ($B_{max} \simeq 18000$ gauss) without excessive losses or magnetizing current. This reduces the transformer weight appreciably. The core is designed with high flux density at the nominal system voltage (25 kV); when the voltage rises above the nominal value, the increased losses and magnetizing current are accepted as a short-term condition.

For h.v. control systems the rectifier transformer and the auto-transformer are built with one yoke common to both. This yoke carries only the difference in flux of the two transformers, so that the iron section is reduced with a corresponding weight reduction.

(4.1.3) Shell-Type versus Core-Type Transformers.

The shell-type transformer is usually preferred to the core-type mainly because it provides constructional advantages. In shell transformers the core, in effect, surrounds the coils. The shell and core types are compared by the simplified sketches of Fig. 13.

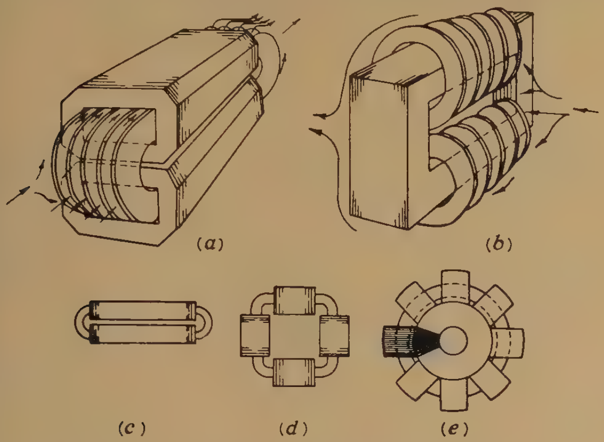


Fig. 13.—Core-type and shell-type transformers.
Arrows indicate oil flow.
(*a*) Shell type.
(*b*) Core type.
(*c*) Shell—2-loop core.
(*d*) Shell—4-loop core.
(*e*) Shell—radial core.

The main advantages of the shell type, Fig. 13(*a*), are:

(*a*) The shape permits a simple design of tank to fit closely round the active parts, thus avoiding wasted space and reducing the volume and weight of oil.

(*b*) The oil flows in clearly defined paths in close contact with the coils, thus promoting effective heat transfer.

(*c*) The core laminations can be clamped together by the two halves of the tank, thus avoiding the use of clamping bolts passing through the core.

(*d*) The shell type is more flexible in shape, as all three dimensions are more or less independent of one another.

In the simplest shell construction there are only two loops of iron core around the rectangular-shaped coils, but this could obviously be increased to four loops.

With circular coils the number of loops can be increased to as many as are desired—this arrangement leading to the radial-core design.

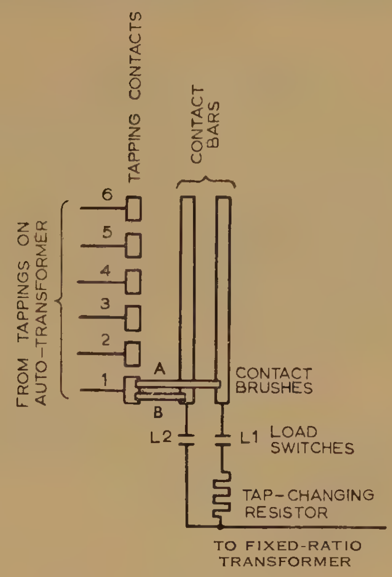
(4.2) Voltage Control-Gear

(4.2.1) H.V. Control.

Fig. 14 shows the connections for a typical h.v. tap-changer, together with a sequence chart. The chart indicates that this particular tap-changer operates in the manner shown step by step in Fig. 6(*b*).

The contact brushes A and B operate off-load and are mounted on a chain-driven carriage, which, together with the contact blocks and contact bars, is housed in an oil-filled casing. Electrical clearances are therefore small, leading to a compact design. All current-making and breaking is handled by the two load switches L1 and L2, which are mechanically operated from the mechanism which drives the carriage. The load switches are air-break units and are thus readily accessible for maintenance. The tap-changer may be operated by a pilot motor or, as on the S.N.C.F. locomotives, by direct manual drive.

The tap-changing impedance is a resistor, which may be fan-cooled since it is in circuit on alternate running notches (2, 4, etc.).



SEQUENCE

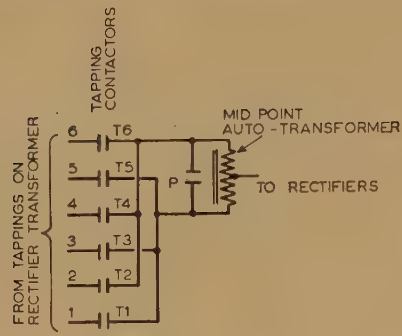
Notch	Contact brushes A (in contact with tapping)	Contact brushes B (in contact with tapping)	Load switches L1	Load switches L2
1	1	1		•
2	2 2 2	1 1 1 1	• •	• • •
3	2 2 2 2	2 2 2	• • •	• •
4	3 3 3	2 2 2 2	• •	• • •
	etc.			

Fig. 14.—Connections and sequence for typical h.v. tap-changer.

(4.2.2) L.V. Control.

The connections for a typical l.v. tap-changer are shown in Fig. 15, together with a sequence chart. This particular tap-changer uses a mid-point auto-transformer as the tap-changing impedance, and the chart indicates that it operates in the manner shown step by step in Fig. 6(*a*).

All the contacts operate on-load and are of the air-break type; they may be operated by a camshaft or they may be in the form of unit switches—usually operated electro-pneumatically. In either case, the contactors are basically similar to those used on d.c. traction equipments, the main change being the lamination of iron parts of electromagnetic blow-out devices.



SEQUENCE

Notch	Contactors						
	P	T1	T2	T3	T4	T5	T6
1	•	•					
2		• •	•				
3	•		• •				
4			• •	•			
5	•			• •			
	etc.						

Fig. 15.—Connections and sequence for typical l.v. tap-changer.

Incidentally, two of the three equipments so far built in Great Britain use camshaft-operated contactors, the camshaft being driven by a pilot motor. The third uses electro-pneumatic unit switches.

Off-load tapping selector contacts, with separate contactors for current-making and breaking, have been used for l.v. control of equipments with a.c. motors. So far as the authors are aware, such schemes have not yet been used for l.v. control of rectifier equipments.

(4.2.3) Mechanical versus Electrical Interlocking.

Short-circuits across sections of the transformer winding must be avoided, therefore the maintaining of correct sequence and timing is more important than for a resistance-controlled d.c. equipment. Consequently, more rigorous interlocking is necessary.

Schemes used or proposed may be divided into three groups: fully mechanical, fully electrical, and mechanical and electrical.

(4.2.3.1) *Fully Mechanical.*

Examples of the fully mechanical system are the h.v. tap-changer described in Section 4.2.1 and the camshaft-operated version of the l.v. tap-changer described in Section 4.2.2 where each contactor operates on load.

The sequence and timing is obtained by simple mechanical means, and the tap-changer can be readily arranged to allow notching back on load from a higher notch to a lower notch.

When power is shut off by the driver, the tap-changer has to run back through all its notches to return to the 'off' position; in doing so, it repeatedly makes and breaks the circulating current drawn by the tap-changing impedance.

(4.2.3.2) *Fully Electrical.*

An example of the fully electrical scheme is the unit switch version of the l.v. tap-changer described in Section 4.2.2 where each contactor operates on load.

The sequence and timing is obtained by electrical interlocks and time-delay devices. If notching back is required, the system becomes more complicated.

When power is shut off by the driver, the unit switches instantly fall into the 'off' position without making and breaking circulating current. Similarly, during a temporary loss of supply, the equipment is immediately ready for starting up again. The tap-changer may also be used for clearing faults or for backing up other fault-clearing devices.

(4.2.3.3) *Mechanical and Electrical.*

An example of the mechanical and electrical arrangement uses mechanically interlocked selector contacts but with electro-pneumatically-operated load switches. The load switches are electrically interlocked with the selector contacts.

The advantages of this scheme are:

(*a*) Mechanical interlocking is provided between those contacts for which correct sequence is vital.
(*b*) During run-back of the tap-changer after power is shut off by the driver, repeated rupturing of circulating current is avoided.
(*c*) Notching back can be arranged reasonably simply.
(*d*) The load switches can be used for clearing faults or for back-up protection.

(4.3) Rectifiers

(4.3.1) Mercury-Arc Rectifiers.

There is a choice between air and water cooling, between single-anode and multi-anode rectifiers, and, with the single-anode type, between ignitrons and excitrons. The multi-anode rectifier, whilst probably being the most economical for substation duty, is not as convenient for use on locomotives as the single-anode rectifier, on account of its size and shape and of the desire to use bridge circuits.

For locomotives, adhesion considerations prohibit the connecting of traction motors in series. The output of the rectifier is required at between 600 and 900 volts, assuming 6-pole motors; at 800 h.p. per axle, this means between 1 100 and 750 amp continuous rating. Such current ratings can conveniently be obtained with small rectifiers by the use of water cooling, the water being pumped through the rectifier cooling jackets and through a fan-cooled radiator. The water is treated with anti-freeze and anti-rust agents, and rubber pipes about 10 ft long are inserted to insulate the rectifier tanks from the radiator and from one another. The water is heated when starting up in cold weather, as it is essential to avoid applications of load at too low a temperature, when 'ion starvation' in the rectifier will cause voltage surges.

Fig. 16 indicates the essential differences between ignitrons and excitrons. In the former a cathode spot is initiated once in every cycle at the correct instant for the firing of the main anode, this cathode spot being formed at the junction of the stationary ignitor and the mercury surface when a pulse of current is passed from the ignitor to the mercury. The pulse is obtained from static circuits, as indicated. The excitron, however, has a cathode spot initiated on the mercury surface by one of the methods normally used in multi-anode rectifiers, and this spot remains burning continuously, the main anode firing whenever it becomes positive relative to the cathode.

The water-cooled ignitron has been used almost exclusively and has given good results. The drawbacks of ignitrons are the rather complicated circuits for firing the ignitors and the possibly limited life of each ignitor compared with that of the rectifier as a whole. For this reason two or three ignitors are usually fitted in each rectifier. These drawbacks are overcome in the excitron, but this type of rectifier needs a cathode insulator and an ignition device, both of which add to its height. The more straight-forward mode of operation of the excitron auxiliaries is in its

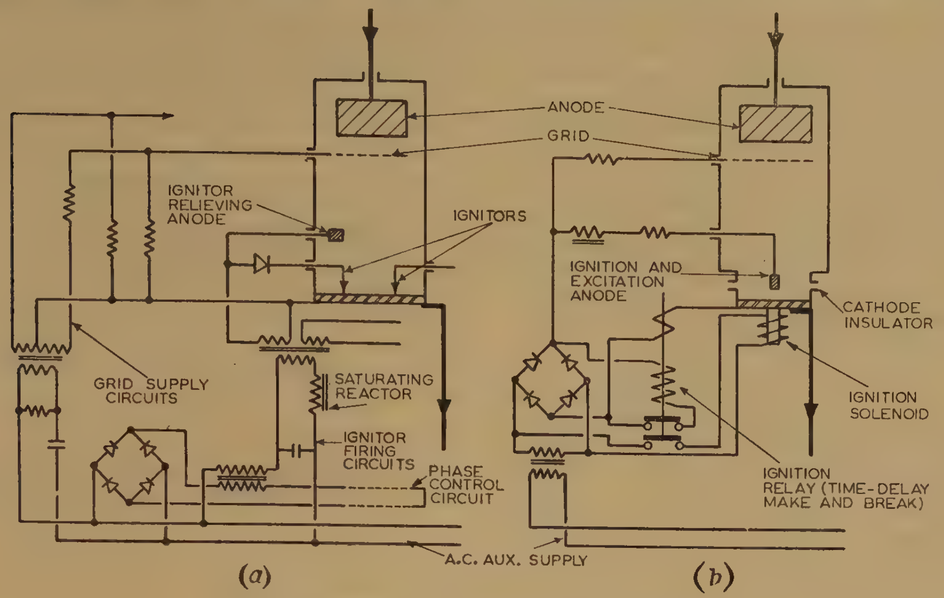


Fig. 16.—Auxiliary circuits for ignitrons and excitrons.

(*a*) Ignitron. (*b*) Excitrons.

favour, but the rectifier construction is somewhat more complex. Needless to say, whatever rectifier is used must be pumpless.

(4.3.2) Semi-Conductor Rectifiers.

Semi-conductor rectifiers, although not competitive in price at present, are being developed rapidly and have a promising future for traction applications. Their greatest asset is simplicity, owing to the absence of preheating, excitation and ignition equipment.

Germanium rectifiers do not show any really significant reduction in size compared with the mercury-arc rectifier at the voltages which can be used for traction motors, and there is very little gain in efficiency. Silicon rectifiers, however, can operate up to much higher temperatures than germanium and show considerable savings in space and weight. A set of semi-conductor rectifiers is more flexible in dimensions than a mercury-arc rectifier.

Semi-conductor rectifiers have very short heating time-constants and hence need to be continuously rated for operation at the accelerating current. Fuses are needed to obtain sufficiently high-speed protection to prevent damage to the rectifiers due to faults. At present, the equivalent of grid control is not available with semi-conductor power rectifiers, and hence smooth control of voltage cannot be obtained by the method of Section 3.3.2.2.

(4.4) Traction Motors

As it is found to be quite practicable to use standard series-wound d.c. motors, motor design will not be discussed: it is interesting, however, to consider the effects of the ripple current.

The output of the rectifier contains voltages of all the even harmonics, and consequently there is a current of each of these frequencies in the traction motors, the second-harmonic, i.e. 100 c/s, current being by far the largest. The magnitudes of these alternating currents depend on the harmonic voltages and the total circuit impedance. The harmonic voltages are approximately proportional to the direct voltage. It is usual to increase the circuit impedance by adding a smoothing reactor.

The degree of ripple in the motor current is usually expressed as a percentage, i.e. half the peak-to-peak value of the ripple as a percentage of the mean motor current.

The harmful effects of the ripple can be reduced by increasing the reactor size, but a compromise is necessary as reactors are heavy. A ripple of between 20% and 50% is normally allowed.

Factors due to ripple which increase heating are:

(*a*) Copper losses of the ripple current, including eddy losses.
(*b*) Eddy-current and hysteresis losses in the iron due to pulsating fluxes.

Factors due to ripple current which affect commutation are:

(*c*) Transformer e.m.f.'s in the armature coils due to pulsating main-pole flux.
(*d*) Voltages of self-induction in the armature winding.
(*e*) Magnitude and phase angle of interpole flux.

(4.4.1) Extra Heating due to Ripple.

Excessive heating occurs in main field and interpole field windings unless they are designed for minimum eddy-current and stray losses. This requirement makes it desirable, for example, to use coils on edge.

Tests on a typical motor, regarding armature heating, gave the results shown in Table 2.

Table 2

Rating of Armature with Different Ripple Currents

Degree of ripple	Total r.m.s. current	Mean current rating from tests	Approximate loss in rating	
			Due to (*a*)	Due to (*b*)
%	%	%	%	%
0	100	100	0	0
20	101	95·5	1	3·5
35	103	92	3	5

(4.4.2) Effect of Ripple on Commutation.

A.C. commutator motors suffer from bad commutation at very low speeds, owing to the heavy current circulating through the brushes as a result of the 'transformer e.m.f.' in the short-circuited armature turns. This e.m.f. is of the order of 3 volts, even after the number of poles has been increased to, say, 18. Interpole diverters are used to compensate the transformer e.m.f. at higher speeds but are ineffective at speeds near standstill.

The rectifier-fed d.c. motor, on the other hand, has a trans-

former e.m.f. which is negligible at standstill and which rises approximately proportionally with voltage reaching about 1 volt at full speed. Whilst 6-pole motors have lower transformer e.m.f.'s than 4-pole motors, this is not a primary reason for increasing the number of poles as it is on a.c. motors. Interpole diverters are not used.

Satisfactory commutation is not as easily obtained as with a steady current, owing to the circulating currents in the brushes caused by transformer e.m.f., and owing to the interpole flux not following the pulsations of armature current correctly in magnitude and phase. Ideally, the interpole-flux circuit should be fully laminated and should not become saturated. Nevertheless, standard d.c. traction motors are performing very well on pulsating current.

Tendency to flashover is influenced by the voltage between adjacent commutator bars immediately after they leave the trailing edge of a brush. This voltage will differ in three ways from that on a motor supplied with steady current:

(i) The air-gap flux, which is a combination of main-pole flux and armature-reaction flux, is pulsating, and hence the voltage of rotation of the armature conductors pulsates also.

(ii) The pulsation of the armature-reaction flux causes self-induced voltages to appear between adjacent commutator bars.

(iii) The pulsation of the main-pole flux causes transformer voltages to be induced in the armature conductors.

Fig. 17 shows these voltages plotted for a typical motor with

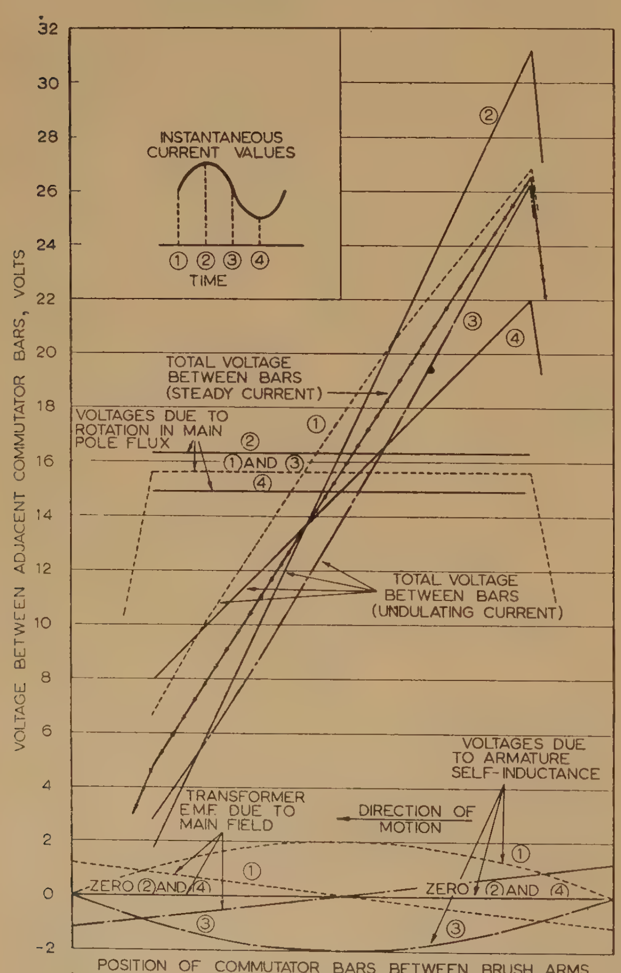


Fig. 17.—Distribution of voltage around the commutator.

35% ripple current, for different positions of the commutator bar between brushes. They are of approximately correct magnitude and are added together with regard to their different time-phasing. It is evident that the main detrimental factor is the peak of curve 2. This is mainly due to the voltage of rotation in the armature-reaction flux at the peak of the armature current ripple. However, in plotting these figures the alleviating effects of magnetic saturation, graded air-gaps and time-lag of main-pole flux have been ignored.

Motors on d.c. systems are generally considered to be most susceptible to flashover when full voltage is suddenly applied after a few seconds off load. A rectifier-fed motor should be more stable because the presence of the series reactor considerably reduces the rate of rise of current and also reduces the voltage initially applied to the motor.

(4.4.3) D.C. Reactor.

The motor inductance is divided between armature, main field and interpole field approximately as shown in Fig. 18. A

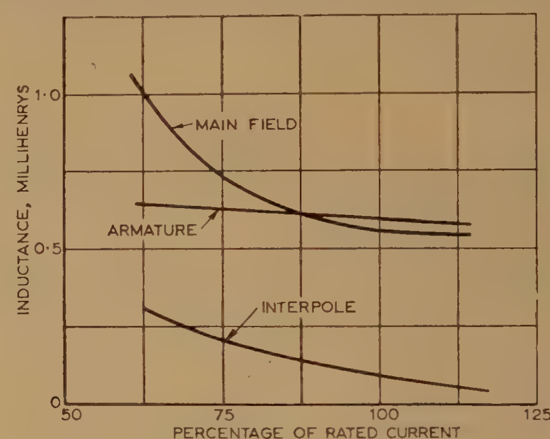


Fig. 18.—Inductance of typical motor.

knowledge of these values is important in calculating the additional inductance necessary to limit the ripple current to the desired value.

The inductance of the series reactor needed per motor in order to obtain various degrees of ripple current is shown in Fig. 19. These d.c. reactors are heavy; for example, a 3 mH

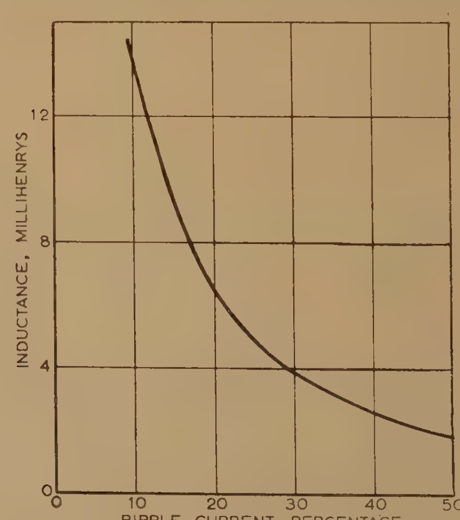


Fig. 19.—Inductance of d.c. reactor to attain different degrees of ripple.

reactor rated at 800 amp weighs about 0·5 ton, and therefore considerations of total weight make ripples as low as 20% practically unattainable. When all relevant factors are considered it is found that ripples of between 30% and 50% must be allowed in order to achieve a minimum overall weight.

(4.4.4) Non-Inductive Field Diverters.

If a non-inductive resistor of, say, 10 times the field circuit resistance is connected across the motor main field, most of the ripple current flows through this diverter and the pulsation of the main flux is reduced by about 80%. Thus factors (*b*) and (*c*) above are considerably reduced, and (*a*) is reduced as far as the main field winding is concerned. On certain motors there is also an improvement in commutation.

Such a diverter need have no adverse effect on output because, if 10% of the mean current is diverted along with the ripple current, the field turns can be increased by 10%.

When a diverter is used it seems reasonable to base the reduction in rating on factor (*a*) only, and hence a larger ripple current may be allowed or conversely a greater rating assigned to the motor.

As the diverter resistance is reduced, and the number of field turns increased to maintain the field strength unchanged, the losses in the diverter decrease to a minimum and then increase again. This minimum value of losses occurs when about 10%–20% of the total direct current flows in the diverter. There is an upper limit to the amount of diverter current which can be allowed because of danger of motor flashover under transient conditions.

The addition of a diverter reduces armature and main field heating and may improve commutation, but it also reduces the circuit inductance and hence increases the ripple current. Unless a larger reactor is used there are then more interpole heating and higher peak voltages on the commutator and perhaps no improvement in commutation. Whether or not a diverter is of advantage will depend on the particular limiting factors on the motor.

Although such a diverter as this has not yet been applied to locomotives, it is in use on the motor-coaches on the Lancaster–Morecambe–Heysham line of British Railways and forms a valuable method of extracting a little more rated power out of a given motor armature.

(5) PERFORMANCE

(5.1) Traction Motor

The motor-armature diameter d_a and length l_a are normally determined by the following three factors:

Maximum operating speed, U.
Rated tractive effort, T_r.
Rated speed (highest value) at average line voltage, $u_{r\,max}$.

The speed at which the rated tractive effort is required, together with that tractive effort, gives the required rated horse-power. For any given armature dimensions the rated speed, and therefore the horse-power, can be increased towards its highest value by raising the voltage or choosing a winding with fewer armature conductors. This highest possible rated horse-power is obtained when the rated speed is raised to the point where the voltage between adjacent commutator bars has reached the limit imposed by risk of flashover.

Provided that the gear ratio chosen allows maximum permissible armature speed to be attained, the following relationships apply:

$$d_a \propto T_r u_{r\,max} \text{ (}\propto\text{ highest rated horse-power).}$$

$$d_a l_a \propto T_r U$$

and, therefore,
$$l_a \propto \frac{U}{u_{r\,max}}$$

The above relationships yield the minimum theoretical size of armature independently of the number of poles and the voltage, for a given ampere-conductor per inch loading and flux density of the armature.

A factor not yet mentioned is the required starting tractive effort, but this does not usually determine the armature dimensions. This is because a motor having a reasonably high rated tractive effort will meet the required starting tractive effort as an overload.

(5.2) Rectifiers and Transformer

These will normally be rated for the continuous rated current of the motors as determined from considerations as in Section 3.1.4. Regard must be paid to overloads due to prolonged starts, steep grades, etc., in relation to heating time-constants. Highly rated equipment tends to have short time-constants, because losses increase and thermal mass is reduced. For example, this applies to air-cooled rectifiers, which have smaller thermal capacity than water-cooled ones, and even more to semiconductor rectifiers, which can be damaged by an overload of even a few seconds' duration. A high-reactance transformer may be necessary with germanium rectifiers to limit fault currents, and this would have a detrimental effect on performance.

(5.3) Rated Performance and Line Voltage

The rated performance is that which the locomotive can give at the average line voltage, 22·5 kV for a nominal 25 kV system, on the assumption of sinusoidal voltage and zero supply impedance. However, it is necessary for the equipment to operate satisfactorily at 27·5 kV for limited periods. The equipment must also operate satisfactorily at line voltages of the order of 17 kV.

The tendency of motors to flashover and of rectifiers to backfire is based on the maximum line voltage, i.e. on a power appreciably greater than the rated power. The waveform of the average line voltage is not, in fact, sinusoidal, and rectifiers should ideally be tested with a no-load anode voltage corresponding to 27·5 kV but with sufficient impedance in the a.c. supply to simulate the resistance drop and overlap effects which occur in service. This condition is more severe than testing on 22·5 kV with sine waves.

(5.4) Voltage Regulation of Rectifier Equipment

Calculations of drop in direct voltage at the motor involve both resistive and reactive drops. Resistance calculations are quite straightforward. Reactances cause increase in the angle of overlap of the rectifiers and, according to simple theory assuming infinite d.c. inductance, the percentage direct voltage drop is easily calculated as 0·707 times the percentage reactance. This is sufficiently accurate for performance calculations.

(5.5) Power Factor and Harmonics in the Line

Calculation of power factor and harmonics in the line must be made according to rigorous undulating-current theory if reasonably accurate results are required. This theory is dealt with in the companion paper.[10]

The effect of ripple current upon the locomotive equipment has been discussed earlier, but its effect on the supply network is not considered in detail in the present paper. It is, however, desirable to mention that the value of ripple current chosen by the designer of the locomotive does influence the conditions in the supply network. For example, if the ripple in the direct current is made small by very adequate smoothing, the network

displacement power factor, cos ϕ, is improved but the distortion power factor is made worse because the harmonic currents in the network are greater.

(6) CONCLUSION

The aim of the paper has been to discuss the problems of compromise and co-ordination which the designer of the complete equipment has to cope with in bringing together such diverse items as transformers, tap-changers, rectifiers and traction motors. No attempt has been made to put forward any 'ideal solution'; it is felt that the possibilities for development are too great to allow any existing equipment to qualify for such a title.

(7) ACKNOWLEDGMENTS

The authors wish to thank the English Electric Company, Limited, for permission to publish the paper, and their colleagues within the company for help in its preparation.

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[The discussion on the above paper will be found on page 368.]

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Mar. 1957

CIRCUIT CALCULATIONS FOR RECTIFIER LOCOMOTIVES AND MOTOR-COACHES

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SUMMARY

The increasing use of rectifier locomotives and motor-coaches has focused attention on the limitations of accepted rectifier theory in the calculation of performance of bi-phase and single-phase bridge-connected rectifier circuits. Most industrial rectifier installations exceeding a few kilowatts in rating are supplied from a 3-phase system, and are designed to operate with 6- or 12-phase output on the d.c. side, while sometimes in very large installations it is necessary to operate with up to 72-phase output. In these conventional multi-phase equipments the ripple current, which is associated with undulations in the output voltage, is superimposed on the output direct current, but is sufficiently small to permit, for the purpose of calculation, the assumption of a d.c. circuit of infinite inductance. This assumption leads to considerable simplification of the theory. Unfortunately it is not tenable in the circuits discussed in the paper, as it is found that the presence of the ripple current in the d.c. circuit has a profound effect on the operation of the whole equipment.

The paper outlines the calculations for bi-phase and bridge circuits, based on the accepted 'infinite inductance' theory, and derives the direct voltage at the motor, ripple current in the motor circuit, power factor in the a.c. supply, harmonic currents in the a.c. supply and other related quantities. The inaccuracies in the results of these calculations are pointed out.

A description follows of a new approach to rectifier problems, by means of which solutions to both transient and steady-state problems can be obtained, taking proper account of resistances, inductances and capacitances in all parts of the circuit. The problems are treated as circuit problems, the equilibrium equations being established in terms of mesh currents and expressed as simultaneous first-order differential equations. These are solved by means of a digital electronic computer, Deuce, whose logical facilities are used to take account of the valve action of the rectifying elements.

Results of calculations are supported by tests which were carried out in conjunction with British Railways on the Lancaster–Morecambe–Heysham section. A description of this electrification has appeared elsewhere.[12] The operation of rectifier locomotives is discussed in the light of further calculations based on variations of a typical design.

LIST OF SYMBOLS

I_d = Direct current output.
n = Harmonic number.
V_p = R.M.S. contact-wire voltage at no-load.
ω = System frequency $\times 2\pi$.
k = Rectifier transformer turns ratio ($= V_{so}/V_p$).
x_{pc} = Percentage reactance of total commutating circuit derived by short-circuiting all rectifiers and open-circuiting all d.c. load circuits. The percentage reactance is that which would be measured by injecting a current at source equivalent to the rectifier transformer rated primary apparent power (kVA) at the source voltage, and expressing the voltage required as a percentage of the source voltage. The primary apparent power is that calculated from the simple 'infinite inductance' theory.
μ = Angle of overlap.
α = Inherent delay angle.
X_{sup} = Loop reactance of 3-phase supply network.
x_{sup} = Percentage reactance of 3-phase supply network (on primary apparent power of rectifier transformer).
R_{sup} = Loop resistance of 3-phase supply network.
X_{sub} = Reactance of substation transformer.
x_{sub} = Percentage reactance of substation transformer (on primary apparent power of rectifier transformer).
R_{sub} = Resistance of substation transformer.
X_{con} = Loop reactance of contact wire.
x_{con} = Percentage reactance of contact wire (on primary apparent power of rectifier transformer).
R_{con} = Loop resistance of contact wire.
R_p = Total resistance up to pantograph.
$= R_{sup} + R_{sub} + R_{con}$.
X_p = Total reactance up to pantograph.
$= X_{sup} + X_{sub} + X_{con}$.
R_{pp} = Resistance of primary winding of rectifier transformer.
R_{ss} = Resistance of each secondary winding of rectifier transformer (bi-phase).
= Resistance of secondary winding of rectifier transformer (bridge).
x'_{sc} = Percentage reactance of rectifier transformer with one secondary winding short-circuited (on primary apparent power; bi-phase).
x_{sc} = Percentage reactance of rectifier transformer with two secondary windings short-circuited (on primary apparent power; bi-phase).
= Percentage reactance of rectifier transformer (on primary apparent power; bridge).
X_a = Reactance of anode circuit (external to rectifier transformer); see Figs. 2 and 3.
R_{ma} = Resistance of d.c. motor armature.
R_{mi} = Resistance of d.c. motor interpoles.
R_{mf} = Resistance of d.c. motor field.
R_{md} = Resistance of d.c. motor field diverter.
L_m = Inductance of d.c. motor.
L_{sr} = Inductance of series reactor.
L_d = Inductance of d.c. circuit.
R_{sr} = Resistance of series reactor.
v_x = D.C.-side voltage drop due to commutating reactance.
v_{cu} = D.C.-side voltage drop due to resistance.
v_{arc} = Rectifier arc drop.
R_d = Total resistance of d.c. circuit (to direct current).
R_a = Resistance of anode circuit (external to rectifier transformer); see Figs. 2 and 3.
V_{so} = R.M.S. voltage across each secondary winding of rectifier transformer on open-circuit (bi-phase).
= R.M.S. voltage across complete secondary winding of rectifier transformer on open-circuit (bridge).

(1) INTRODUCTION

In order to understand the operation of rectifier locomotives, it is necessary to know how to calculate the performance of a typical system comprising rectifiers feeding a d.c. circuit, the

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rectifiers being fed from a 3-phase supply system through a substation transformer, an overhead contact wire and a rectifier transformer, as shown for a bi-phase installation in Fig. 1. The circuit constants of such a system can be lumped together to form a basic circuit, as shown in Fig. 2. The general procedure will be to consider the operation of a rectifier system proceeding

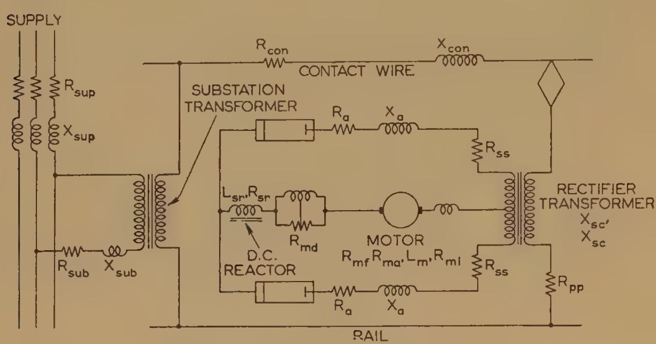

Fig. 1.—Typical circuit (bi-phase).

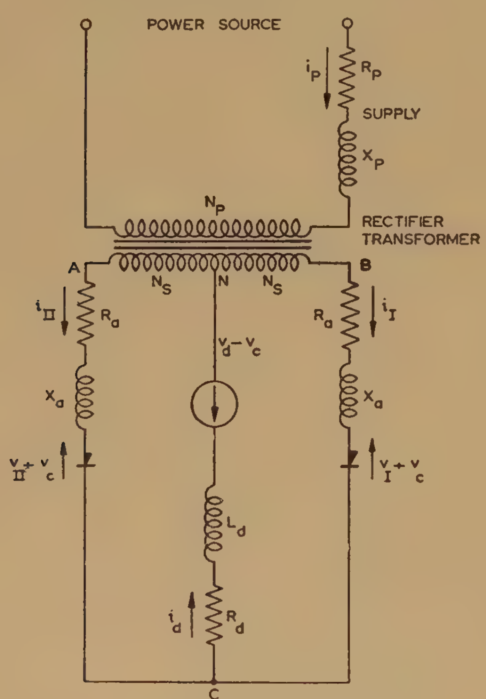

Fig. 2.—Equivalent bi-phase circuit.

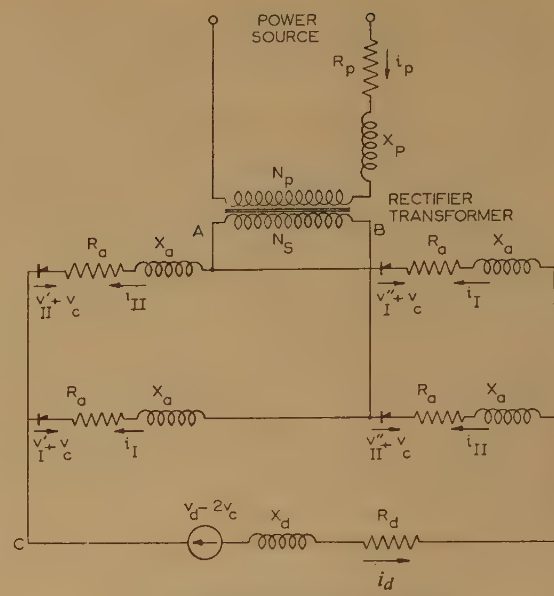

Fig. 3.—Equivalent bridge circuit.

A large variety of circuits can be designed for rectifier locomotives, but they are all based on either the simple bi-phase circuit (Fig. 2) or the simple bridge circuit (Fig. 3). These two basic circuits only will be considered in the paper, while practical circuits derived from these will be found in the companion paper.[6]

(1.1.1) Bi-phase Circuit.

In the bi-phase circuit, as shown in Fig. 2, each secondary transformer phase will carry the full direct current for half a

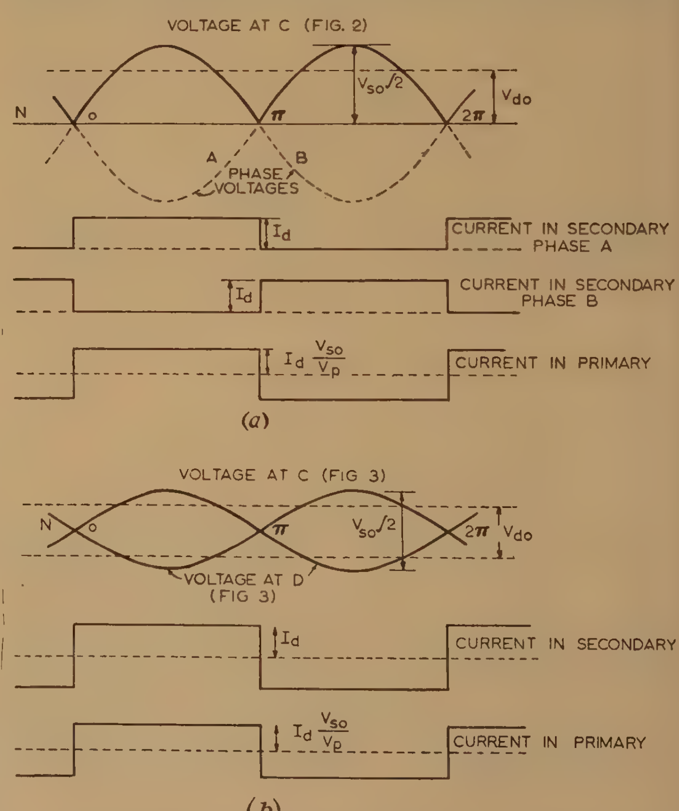

Fig. 4.—Voltages and currents for basic circuits according to simple 'infinite-inductance' theory.

through several discrete stages, to show how the most refined theory is derived. The first and second stages have been dealt with in detail, with more emphasis on multi-phase equipments, in a previous paper.[8] The first stage is described below, in relation to single-phase installations.

(1.1) Simple (Infinite-Inductance) Theory

The simple infinite-inductance theory is a study of circuit operation based on ideal circuit components, i.e. all losses, reactances and magnetizing currents are neglected. Furthermore, the d.c. side is assumed to be infinitely inductive. Based on these assumptions, simple relations for the various circuit quantities can be easily derived in line with conventional rectifier theory.

Table 1

EXPRESSIONS AND EXAMPLE FOR BI-PHASE RECTIFIER UNDER SIMPLE INFINITE-INDUCTANCE THEORY

Quantity	Expression	Expression number	Example
A.C.-side primary voltage (no-load), volts	V_p	—	6 600
D.C.-side power output, kW	$P_{do} = V_{do} I_d$	—	847
D.C.-side voltage, volts	V_{do}	—	1 463
D.C.-side current, amp	I_d	—	578
Secondary voltage, volts	$V_{so} = \frac{V_{do}\pi}{2\sqrt{2}}$	1	1 628
*R.M.S. fundamental component of current in secondary winding, amp	$I_{1so} = \frac{I_d\sqrt{2}}{\pi}$	2	260
Phase of r.m.s. fundamental component of current in secondary winding, degrees	$\gamma_{1so} = \text{arc tan}\left(\frac{\sin \pi}{1 - \cos \pi}\right)$	3	0
Total secondary power, kW	$P_{so} = 2I_{1so}V_{so}$	4	847
R.M.S. fundamental component of current in primary winding, amp	$I_{1po} = \frac{I_d 2\sqrt{(2)} V_{so}}{\pi V_p}$	5	128
Phase of r.m.s. fundamental component of current in primary winding, degrees	$\gamma_{1so} = \text{arc tan}\left(\frac{\sin \pi}{1 - \cos \pi}\right)$	6	0
Total primary power, kW	$P_{po} = I_{1po}V_p$	7	847
R.M.S. harmonic currents in primary (odd harmonics only present), amp	$I_{npo} = \frac{I_{1po}}{n}$	8	$\frac{128}{n}$
Phase angle of harmonic currents in primary, degrees	$\gamma_{npo} = \text{arc tan}\left(\frac{\sin n\pi}{1 - \cos n\pi}\right)$	9	$\frac{\pi}{2}(1 - n)$
Rectifier transformer primary rating, kVA	$K_{op} = 1{\cdot}11\, P_{do}$	10	940
*Rectifier transformer secondary rating, kVA	$K_{os} = 1{\cdot}57\, P_{do}$	11	1 329
*Rectifier transformer mean rating, kVA	$K_{om} = 1{\cdot}34\, P_{do}$	12	1 135
Rectifier mean current (per valve in the basic circuit), amp	$I_{mso} = \frac{I_d}{2}$	13	289
*Rectifier peak inverse voltage, volts	$V_{pi} = \pi V_{do}$	14	4 600
R.M.S. nth-harmonic voltage across motor circuit (even harmonics only present), volts	$V_{ndo} = V_{do}\frac{\sqrt{2}}{n^2 - 1}$	15	—
Percentage d.c.-side regulation due to reactance (as percentage of V_{do})	$v_x = 0{\cdot}707\, x_{pc}$	16	—

* Not applicable to bridge. See Table 2.

cycle, followed in a similar manner by the second phase. The mean d.c. output voltage is given by the mean value V_{do} of the cathode-to-neutral voltage in Fig. 4(a); the waveshape of current in each part of the circuit is given in the same Figure. The assumption of zero commutating reactance and infinite d.c.-side inductance ensures that the anode currents are rectangular in shape. Analysis of the output voltage wave and the anode currents enables the complete characteristics of the circuit to be obtained, as the Fourier components of the anode currents can be reflected through the transformer to give the corresponding components in the a.c. supply system. Table 1 contains expressions for various features of performance, and numerical values are given for a practical example based on conditions for an actual test on the Lancaster–Morecambe–Heysham system of British Railways.

(1.1.2) **Bridge Circuit.**

In the bridge circuit, shown in Fig. 3, the current flows from the transformer through one rectifier, then through the d.c. load and back to the other end of the transformer winding through a second rectifier. On reversal of the alternating voltage in the transformer, the current flows in the opposite direction in the transformer secondary winding and through a different pair of rectifiers. Thus, unlike that in the bi-phase circuit, the current in the secondary of the transformer has no mean component. The expressions given in Table 1 can all be used for bridge

circuits, with the exception of those indicated. Table 2 gives the additional expressions.

Table 2

EXPRESSIONS AND EXAMPLE FOR BRIDGE RECTIFIER UNDER SIMPLE INFINITE-INDUCTANCE THEORY (AS TABLE 1, EXCEPT FOR THE FOLLOWING)

Quantity	Expression	Expression number
R.M.S. fundamental component of current in secondary windings, amp	$I_{1so} = \frac{I_d 2\sqrt{2}}{\pi}$	17
Rectifier transformer secondary rating, kVA	$K_{os} = 1 \cdot 11 P_{do}$	18
Rectifier transformer mean rating, kVA	$K_{om} = 1 \cdot 11 P_{do}$	19
Rectifier peak inverse votage, volts	$V_{pi} = \frac{\pi}{2} V_{do}$	20

Note: V_{so} is *total* secondary winding voltage for *bridge* when used in expressions of Table 1.

The direct voltage on the rectifier side of the infinite inductance is equal to the difference between the two sine waves shown in Fig. 4(*b*). The open-circuit voltage V_{so} is defined as being associated with the complete secondary winding, so that bi-phase and bridge installations having the same value of V_{so} have the same mean output voltage V_{do}.

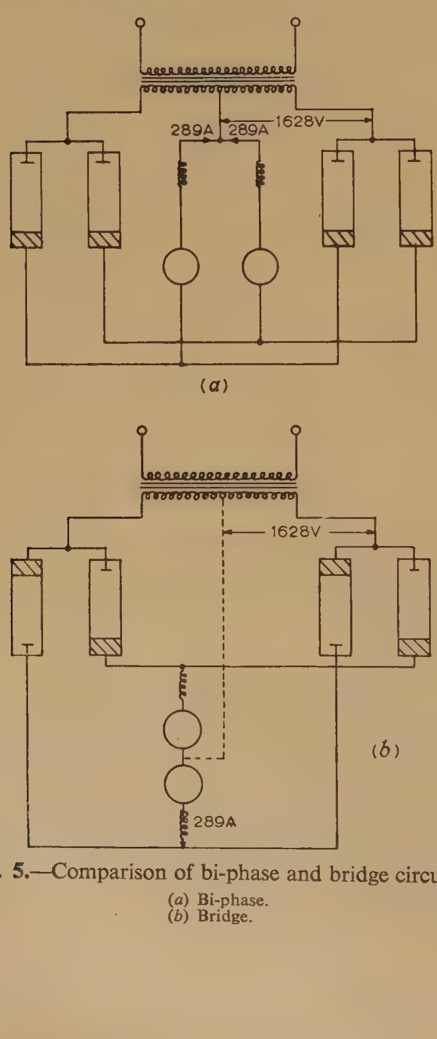

Fig. 5.—Comparison of bi-phase and bridge circuits.
(*a*) Bi-phase.
(*b*) Bridge.

Comparison between Tables 1 and 2 will show that for the bridge circuit there is a saving of 17% on the mean apparent power of the rectifier transformer, and also the valves are worked at half the peak inverse voltage for the same direct voltage, although of course, four valves are required against the two required for bi-phase. As a means of comparison, consider the two circuits shown in Fig. 5, where for each connection two motors are used. If the motors are used in the equivalent parallel circuit in the bi-phase case, and in series in the bridge case, then the two equipments are identical as far as motor current, motor voltage, harmonic voltage in the motors, mean rectifier current, rectifier peak inverse voltage, supply current and supply-current harmonics are concerned. In fact, the only difference is the decrease of 17% in the mean apparent power of the rectifier transformer for the bridge case. Other practical differences between the two connections are given in the companion paper.

(2) 'INFINITE INDUCTANCE' THEORY

This Section refers specifically to bi-phase circuits, but the equations apply equally to bridge circuits.

It is shown in Fig. 6 that the direct voltage, the anode currents and the primary current are modified from those indicated in Fig. 4(*a*), when allowance is made for reactance in a bi-phase circuit. The period of commutation is usually represented by the angle of overlap μ, which is given by

$$\mu = 2 \arcsin \sqrt{\frac{0 \cdot 707 x_{pc} L}{100}} \quad . \quad . \quad . \quad . \quad (21)$$

The percentage reactance includes the reactances of the 3-phase supply system, the substation transformer, the overhead contact wire, the rectifier transformer and any reactance on the secondary side in the commutating path. L is the fraction of full load at which the value of μ is required.

(2.1) Regulation

The periods of commutation cause a reduction of the mean direct output voltage by the mean of the shaded areas shown in Fig. 6(*a*). This reduction v_x is given by

$$v_x = V_{do} \sin^2 (\mu/2) \quad . \quad . \quad . \quad . \quad . \quad (22)$$

For a given commutating reactance, v_x increases linearly with the load current. This follows from eqns. (21) and (22).

Allowance is made for copper losses by summating the I^2R losses throughout the equipment, and dividing the total by the load current to give an equivalent direct voltage drop, v_{cu}. This voltage drop is also proportional to the load current.

The arc voltage drop, v_{arc}, of the rectifier is almost constant over the current range for mercury-arc rectifiers, but may vary for different types of rectifier. The mean direct voltage at any load can be calculated, taking into account the three factors mentioned above, as

$$V_d = V_{do} - v_x - v_{cu} - v_{arc} \quad . \quad . \quad . \quad (23)$$

(2.2) Power Factor

The 'power factor' considered throughout the paper is as defined in Appendix C of B.S.1698: 1950, and is in fact the displacement factor, cos ϕ, of the fundamental components of voltage and current.

Fig. 6 indicates the waveshapes of the anode currents which, by comparison with Fig. 4(*a*), clearly show that the 'centre of gravity' of the fundamental component of a block of anode current has been shifted to the right, i.e. delayed with respect to the supply voltage. It follows that the fundamental component

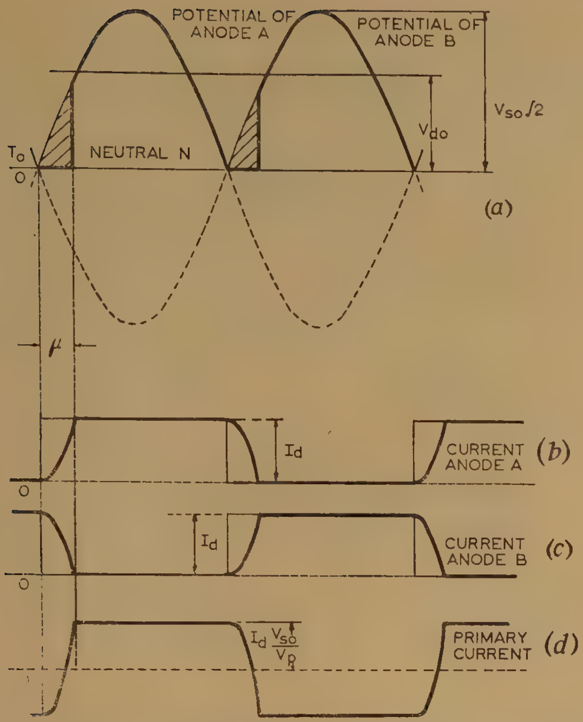

Fig. 6.—Voltages and currents for bi-phase circuit according to 'infinite-inductance' theory.

of primary current is correspondingly delayed, resulting in a reduction of power factor.

Expressions[8] are given below for the active and reactive components of primary current:

$$\text{Active component} = I_{1p\mu p} = I_d \frac{2\sqrt{2}}{\pi} \frac{V_{so}}{V_p} \cos^2 (\mu/2) \quad (24)$$

$$\text{Reactive component} = I_{1p\mu r} = I_d \frac{2\sqrt{2}}{\pi} \frac{V_{so}}{V_p} \frac{2\mu - \sin 2\mu}{4(1 - \cos \mu)} \quad (25)$$

The active and reactive components thus calculated can be corrected by the addition of auxiliary load and transformer magnetizing currents, the power factor being calculated in the usual way.

(2.3) Harmonic Voltage in the D.C. Circuit

Assuming zero commutating reactance, the harmonic content of the direct voltage on the rectifier side of the infinite inductance is given by eqn. (15) (Table 1). The introduction of commutating reactance, with its consequent angle of overlap, modifies the voltage waveform to that shown in Fig. 6(*a*). Under these conditions the expression[8] for the r.m.s. harmonic voltage is modified to

$$V_{nd\mu} = V_{do} \frac{1}{\sqrt{(2)}(n^2 - 1)} \times \sqrt{[(\cos n\mu + \cos \mu)^2 + (\sin n\mu + n \sin \mu)^2]} \quad (26)$$

It should be noted that, since the d.c. circuit is still assumed to be infinitely inductive, the presence of these harmonic voltages should not cause any harmonic current to flow in the motor circuit. However, in order to make a rough estimate of the degree of ripple current in the motor, it is often accepted that the motor circuit is infinitely inductive for the purpose of calculating the harmonic voltages, but that it can be considered to have a finite inductance when calculating the ripple current, using these voltages. It is realized that this treatment is far from rigorous, and is used only for approximate calculations. The peak value of the nth harmonic current in the motor circuit is given by

$$I_{nd\mu} = \frac{\sqrt{(2)} V_{nd\mu}}{n\omega L_d} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

It is sometimes convenient to express the amount of fluctuation in the rectified output current by the percentage ripple, defined as

$$\frac{\text{Maximum value} - \text{Minimum value}}{2 \times \text{Mean value}} \times 100$$

This is usually very close to the percentage second harmonic, defined as

$$\frac{\text{Peak value of second harmonic}}{\text{Mean value}}$$

(2.4) Harmonic Currents in the Primary Circuit

Table 1 gives the amplitude and phase of each primary-current harmonic calculated on the assumption of no commutating reactance. The introduction of commutating reactance causes each harmonic to vary in amplitude[8] according to the following equation:

$$I_{np\mu} = I_d \frac{2\sqrt{2}}{\pi n} \frac{V_{so}}{V_p} \sin \frac{n\pi}{2} \times \frac{\sqrt{[n^2 \sin^2 \mu + \cos^2 \mu + 1 - 2(n \sin n\mu \sin \mu + \cos n\mu \cos \mu)]}}{(n^2 - 1)(1 - \cos \mu)} \quad . \quad . \quad . \quad . \quad (28)$$

It is worth noting that as the harmonic number n is increased, the amplitude of the harmonic decreases, according to the simple theory, as $1/n$; it is further attenuated by the effect of overlap, particularly for the higher harmonics.

(2.5) Limitations of the Infinite-Inductance Theory

The limitations of the infinite-inductance theory will be best understood by means of an example which compares calculated results with those of an actual test. Consider first Table 3, which shows the calculations for the same example as used in Table 1, but in which the total commutating reactance is now taken into account.

In Table 3, the necessary expressions are given and their references quoted. The calculations in this Table, therefore, represent the way in which the electrical performance of the bi-phase rectifier circuit would be calculated, if the assumption of infinite inductance in the d.c. circuit were accepted.

Fig. 1 is the equivalent circuit relative to Tables 1 and 3, and represents the conditions during a test carried out on the Lancaster–Morecambe–Heysham system. The electrical equipment on the motor-coach has been simplified in the Figure to form a basic circuit. The train was accelerating near Morecambe, and simultaneous oscillographic and meter readings were taken on the train and in the substation at Lancaster. At the instant the records were taken, the direct current delivered was 578 amp with the transformer on a tapping to give $V_{so} = 1\,628$ volts (Figs. 7 and 8). The percentage reactance of the commutating circuit, including the 3-phase supply system, substation transformer, contact-wire, rectifier transformer and commutating-circuit reactance connected to the rectifier transformer secondary, was estimated to be 19·6% on the rectifier transformer primary apparent power.

Table 3

EXPRESSIONS AND EXAMPLE FOR BI-PHASE RECTIFIER UNDER INFINITE-INDUCTANCE THEORY

Quantity	Expression	Expression number	Example
A.C.-side primary voltage (no load), volts	V_p	—	6 600
Secondary (anode) voltage (no load), volts	V_{so}	—	1 628
D.C.-side current, amp	I_d	—	578
Total reactance of commutating path	x_{pc}	—	19·6%
Angle of overlap, degrees	μ	**21**	44
Rectifier e.m.f., volts	$V_{do} = V_{so}\frac{2\sqrt{2}}{\pi}$	**1**	1 463
R.M.S. fundamental component of current in primary winding (power component) $\mu = 44$, amp	$I_{1p\mu p}$	**24**	110
R.M.S. fundamental component of current in primary winding (reactive component), $\mu = 44$, amp	$I_{1p\mu r}$	**25**	60
Copper losses:			
3-phase supply, substation transformer and contact wire, kW	$\left(I_d\frac{V_{so}}{V_p}\right)^2 R_p \times 10^{-3}$	—	58·7
Rectifier transformer primary, kW	$\left(I_d\frac{V_{so}}{V_p}\right)^2 R_{pp} \times 10^{-3}$	—	6·0
Rectifier transformer secondary, kW	$\left(\frac{I_d}{\sqrt{2}}\right)^2 R_{ss}2 \times 10^{-3}$	—	8·8
D.C. motors and d.c. reactor, kW	$I_d^2 R_d \times 10^{-3}$	—	36·1
Total loss, kW	ΣP_{cu}	—	109·6
D.C.-side voltage drop (copper loss), volts	$v_{cu} = \frac{\Sigma P_{cu}}{I_d}$	—	190
D.C.-side voltage drop (reactance), volts	$v_x = V_{do}\sin^2(\mu/2)$	**22**	208
D.C.-side voltage drop (rectifier arc), volts	v_{arc}	—	20
Total d.c.-side voltage drop, volts	Σv	—	418
Motor back-e.m.f., volts	$V_m = V_{do} - \Sigma v$	—	1 045
Power output, kW	$V_m I_d \times 10^{-3}$	—	604
Copper losses, kW	ΣP_{cu}	—	110
Arc losses, kW	$P_{arc} = I_d v_{arc} \times 10^{-3}$	—	12
Total (cf. line below), kW		—	726
Power input, kW	$V_p I_{1p\mu p} \times 10^{-3}$	**24**	726
Power factor at source		**24** **25**	0·88
R.M.S. harmonics in contact wire:			
Third r.m.s. value, amp	I_{3pu}	**28**	36·0
Fifth r.m.s. value, amp	I_{5pu}	**28**	16·4
Seventh r.m.s. value, amp	I_{7pu}	**28**	7·9
Ninth r.m.s. value, amp	I_{9pu}	**28**	3·7
Eleventh r.m.s. value, amp	I_{11pu}	**28**	2·5
Thirteenth r.m.s. value, amp	I_{13pu}	**28**	2·0
Fifteenth r.m.s. value, amp	I_{15pu}	**28**	1·6
Peak harmonic currents in motor circuits:			
Second peak value, amp	I_{2du}	**27**	359
Fourth peak value, amp	I_{4du}	**27**	40

Numbers in bold-face type refer to expressions in the text.

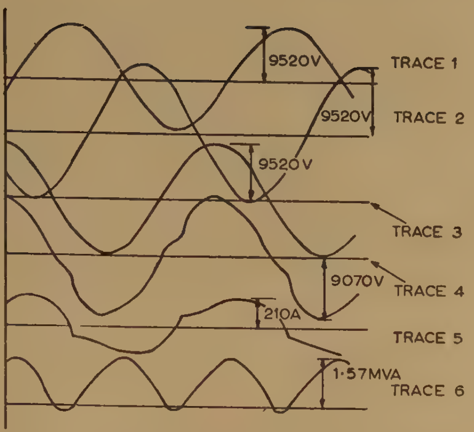

Fig. 7.—Lancaster–Morecambe–Heysham tests.

Test III(1). Oscillogram recorded at substation.
Trace 1. Primary voltage R–Y. Trace 4. Secondary voltage.
Trace 2. Primary voltage Y–B. Trace 5. Secondary current.
Trace 3. Primary voltage B–R. Trace 6. Secondary instantaneous power.

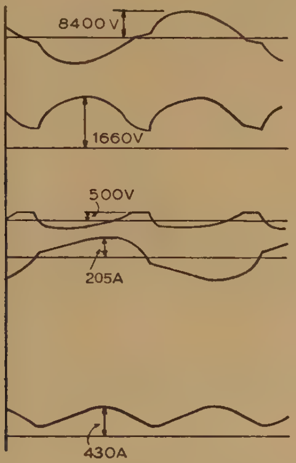

Fig. 8.—Lancaster–Morecambe–Heysham tests.

Test III(1). Oscillogram recorded on train.
Trace 1. Line voltage. Trace 3. Reactor voltage.
Trace 2. Voltage across two motors in series. Trace 4. Line current.
Trace 5. Direct current.

A comparison was made between the calculated and the measured values, the important ones being compared in Table 4. The main point of interest is that if the measured values (column B) are compared with the calculated values (column A) for the same mean output current, the angle of overlap is very much lower, the ripple current in the motors is lower, the line current is higher, the line harmonics are all lower and the power factors are lower. Since the measured angle of overlap was low, it was surprising to find that the direct voltage measured at the motors was almost as calculated. These discrepancies between measured and calculated values, which had been observed in previous tests, provided the reason for this extensive investigation.

It is interesting to note that the harmonic content in the primary current is much less than would be calculated by the 'simple' theory. The amplitudes of the third, fifth, seventh and ninth harmonics as percentages of the r.m.s. line current were found to be 13·7%, 6·2%, 4·1% and 2·2%, the corresponding values according to the 'simple' theory being 30%, 18%, 13% and 10%; (note that the r.m.s. value of the fundamental component is 0·9 times the total r.m.s. value).

Table 4

Comparison of Test Results with Calculations by Infinite-Inductance Theory and Deuce

Test III(1) at Lancaster–Morecambe–Heysham

	A	B	C
A.C.-side primary voltage (no-load), volts	6 600	6 600	6 600
Secondary (anode) voltage (no-load), volts	1 628	1 628	1 628
D.C.-side current, amp	578	578	578
Angle of overlap, degrees	44	27·5	28·1
Percentage ripple current in d.c. motors, $\frac{I_{2d\mu}}{I_d} \times 100$	62%	43%	45%
Inherent delay angle, degrees ..	—	—	7
R.M.S. line current corrected for magnetizing current and train heating, amp	141	150	157
Power factor ($\cos\phi$) at train ..	0·91	0·88	0·87
Power factor at substation output to contact wire	0·89	0·85	0·84
Power factor ($\cos\phi$) at source ..	0·86	—	0·81
D.C. voltage at motors, volts ..	1 110	1 138	1 152
R.M.S. harmonic currents (percentage of r.m.s. contact-wire-currents):			
Third harmonic	25·7%	13·7%	11·4%
Fifth harmonic	11·7%	6·2%	5·9%
Seventh harmonic	5·6%	4·1%	3·6%
Ninth harmonic	2·6%	2·2%	2·3%
Eleventh harmonic	1·8%	1·9%	1·9%
Thirteenth harmonic	1·4%	0·8%	1·0%
Fifteenth harmonic	1·1%	0·3%	0·8%
Peak second-harmonic current in d.c. motors, amp	359	250	259
Peak fourth-harmonic current in d.c. motors, amp	40	22	39

Column A was calculated by infinite-inductance theory.
Column B was deduced from measurements of test III(1) at Lancaster–Morecambe–Heysham.
Column C was calculated by Deuce.

Both sets of calculated quantities (columns A and C) are corrected for train auxiliary load and transformer magnetizing currents.

The discrepancies between calculated and measured results can be attributed to the fact that the ripple current which flows in the d.c. circuit has a profound effect on the rectifier commutation conditions, making its presence felt in two ways:

(*a*) Commutation between anodes does not start at the intersection of the two sine waves of the no-load anode voltage, but is delayed by an angle α, owing to the distortion of these voltages as a result of the reflected motor ripple current flowing in the rectifier transformer and supply system.

(*b*) The angle of overlap as calculated by the infinite-inductance theory is no longer correct, since that theory implies that the direct current is constant.

(3) RIGOROUS APPROACH

The shortcomings of the accepted theory indicated that a more comprehensive approach to single-phase rectifier problems was needed. Work had already been done on the general problem of circuits containing switches or rectifying elements, a description of which has been given elsewhere.[4] Resistances, inductances and capacitances in all parts of the circuit may be taken into account, and both transient and steady-state problems are amenable to solution. A brief account follows of the application of the method to single-phase rectifier installations.

In the Appendix are derived the equilibrium equations [see eqn. (30)] for bi-phase and bridge installations in terms of the

anode currents. The analysis is based on the circuits shown in Figs. 2 and 3; capacitances have been ignored in the interests of simplicity. The equations, which are simultaneous first-order differential equations, take no account of the fact that the anode currents are unidirectional. This is done by deriving from eqn. (30) a set of equations for each of the four possible states of conduction. The four states are:

No anodes conducting.
Anode(s) I conducting.
Anode(s) II conducting.
Anodes I and II conducting.

These equations yield solutions for the anode currents and the values of the anode-to-cathode voltages. A programme has been made for the digital computer, which in effect examines the anode currents and the anode-to-cathode voltages, selects the appropriate set of equations, solves them for one step of the step-by-step integration and repeats the process. Additional features are available so that, in effect, grid impulses of any delay and duration can be taken into account. When desired, the results of the programme can be analysed into harmonic components by a separate programme. Steady-state solutions are found by starting from arbitrary initial conditions and allowing the solution to continue until conditions are repeated every cycle. This approach to rectifier problems is feasible only if high-speed computing facilities are available.

(3.1) Circuit Properties

Details of the circuit analysis are given in the Appendix. An account follows of the way in which various components of a traction system are represented in the analysis.

The power system is represented by its loop impedance, as seen from the primary of the substation transformer, the substation transformer by its short-circuit impedance and the contact wire by its impedance up to the train at the instant in question. Bi-phase rectifier transformers are represented by two reactances X_{sc} and X'_{sc}, these being the short-circuit reactances measured from the primary terminals when the whole and one-half of the secondary, respectively, are short-circuited. In this way proper account is taken of the leakage coupling between the halves of the secondary winding. Bridge-rectifier transformers are represented by their short-circuit reactance X_{sc}.

The traction motors of the Lancaster–Morecambe–Heysham coaches were fitted with field diverters of a value such that a large percentage of the direct current went through the motor field winding, while almost all of the harmonic current went through the diverter. This meant that, under steady-state conditions, the field current, the main field flux and the motor back-e.m.f. remained constant, armature reaction being ignored. It follows that only the direct component of armature current contributed to the average power output of the motor. Such a motor can be represented by a back-e.m.f., v_b, in series with an inductance, L_m, presenting one value of resistance, R_{m1}, to harmonics, and another value, R_m, to direct current. This is equivalent to an inductance L_m in series with a resistance R_{m1} and a back-e.m.f. v_{b1}, where

$$v_{b1} = v_b - i_{av}(R_{m1} - R_m) \quad . \quad . \quad . \quad . \quad (29)$$

and i_{av} is the direct component of motor current. R_m is the resistance of the armature and the interpoles, plus the field winding and diverter in parallel. R_{m1} is the resistance of the armature, interpoles and diverter.

The calculated values of the fundamental active and reactive components of primary current are modified by the addition of an active component corresponding to transformer iron losses and locomotive auxiliary loads, and a reactive component corresponding to transformer magnetizing currents.

(3.2) Correlation between Calculations and Test Results

The parameters for the digital-computer programme were evaluated for circuit conditions corresponding to the test on the Lancaster–Morecambe–Heysham system referred to in Section 2.5. The results of the calculation are given in column C of Table 4 (see Fig. 9). Comparison between the calculated and the measured values shows a much better correspondence than was previously obtained by the infinite-inductance theory. In Table 5, comparison is made between calculated and measured results for a

Table 5

COMPARISON OF MEASURED AND CALCULATED (DEUCE) RESULTS FOR FOUR TESTS ON THE LANCASTER–MORECAMBE–HEYSHAM LINE

C = Calculated. M = Measured.	C	M	C	M	C	M	C	M
Test number	III(2)		VI(1)		VI(2)		VII(1)	
Train location—distance from substation, miles	6·1	6·1	4·7	4·7	4·7	4·7	1·0	1·0
Total d.c. traction motor current, amp	319	319	324	324	599	599	538	538
Total d.c. circuit inductance, mH	6·53	6·53	2·78	2·78	2·31	2·31	2·83	2·83
Inherent delay angle, degrees	8·4	—	28·1*	—	14·1	—	4·2	—
Angle of overlap, degrees	16	15	0	0	11	13	23	25
Peak value of second-harmonic current in motors, amp	210	206	318	324	419	418	207	216
Peak value of fourth-harmonic current in motors, amp	29	28	40	34	67	70	28	42
Percentage ripple current in motors	66%	65%	98%	100%	70%	70%	38%	40%
Total r.m.s. line current (contact wire), amp	97	92	104	105	176	172	72	73
Power factor at train, cos ϕ	0·87	0·87	0·88	0·90	0·89	0·91	0·89	0·90
Power factor at substation, cos ϕ	0·85	0·85	0·87	0·87	0·87	0·88	0·89	0·89
R.M.S. value of 3rd harmonic in line current	12·0%	15·2%	16·4%	16·2%	6·4%	7·9%	11·3%	13·3%
R.M.S. value of 5th harmonic in line current	5·5%	8·5%	6·1%	7·4%	2·6%	4·6%	6·4%	6·0%
R.M.S. value of 7th harmonic in line current	3·6%	4·2%	3·3%	3·4%	1·4%	0·9%	4·1%	4·1%
R.M.S. value of 9th harmonic in line current	2·6%	4·1%	1·9%	1·9%	0·9%	1·4%	2·7%	2·5%
R.M.S. value of 11th harmonic in line current	2·1%	2·5%	1·4%	0·8%	0·6%	1·1%	1·7%	1·5%
R.M.S. value of 13th harmonic in line current	1·8%	3·2%	1·1%	1·2%	0·4%	1·8%	1·1%	1·0%
R.M.S. value of 15th harmonic in line current	1·7%	1·5%	1·0%	0·9%	0·3%	0·8%	0·7%	0·3%
Direct voltage across motors, volts	1284	1270	1382	1345	1193	1160	514	500
Voltage at fundamental frequency at substation, volts	6400	6324	6350	6250	6150	6155	6423	6415
Voltage at fundamental frequency at train, volts	6050	6100	6150	6030	5700	5620	6386	6230

* Discontinuous current in d.c. circuit.

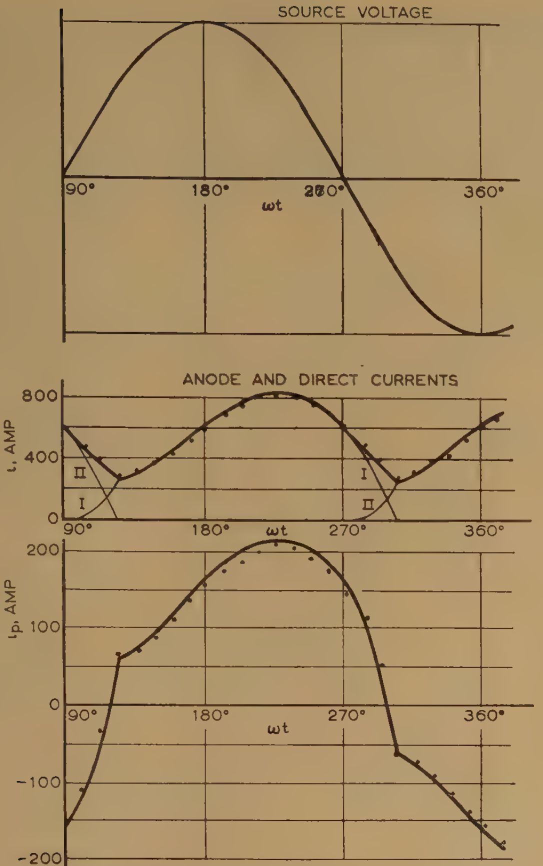

Fig. 9.—Lancaster–Morecambe–Heysham tests.
Test III(1). Currents calculated by Deuce (full lines). Values measured from train oscillogram (dots).

further four test conditions. In each case, the correspondence is good, including test VI(i), where the direct current was discontinuous. The following details are of interest:

(*a*) The inherent delay angle varies over the range of tests from 4·2° to as much as 14·1°. This quantity is, of course, not directly measurable, since the source e.m.f. is not available.

(*b*) The angle of overlap is, for the four cases, appreciably less than would be calculated using the infinite-inductance theory. In test VI(*i*) the direct current was discontinuods, so that overlap is zero.

(*c*) The calculated values of the second-harmonic currents in the d.c. circuit were in good agreement with the measured values.

(*d*) Preliminary calculations revealed that it is essential to take proper account of resistances everywhere in the circuit, in order to predict power factor with sufficient accuracy.

(*e*) Line-current harmonics are expressed as a percentage of the r.m.s. line current. The most important point to note is that they are considerably less than would be expected from the infinite-inductance theory.

(4) CALCULATIONS FOR A TYPICAL LOCOMOTIVE

The good correlation between calculations and the results of the Lancaster–Morecambe–Heysham tests indicated that it was in order to represent the system between the source and the pantograph by a resistance in series with an inductance. It is realized that this may not always be the case. At Lancaster the train was supplied at 6·6 kV from a 6·6 kV 3-phase system. The effects of capacitance will certainly be greater, if, for example, the contact wire is supplied at 25 kV from a 132 kV system, as proposed for the future main-line electrification of British Railways. In the interests of simplicity, however, capacitances have been ignored in the calculations described in the paper. The probable effects of capacitance are discussed later.

The examples described in this Section are based on a tentative design for a 3 000 h.p. locomotive, and indicate how the facilities provided by the digital-computer programme can be used to assess the effects of design modifications. The purpose, in the present case, was to determine the dependence of various performance features on d.c. load current, including power factor and harmonics in the input and output currents for the typical locomotive whose electrical conditions are specified in the Appendix. The results of these calculations are shown graphically in Figs. 10, 11 and 12.

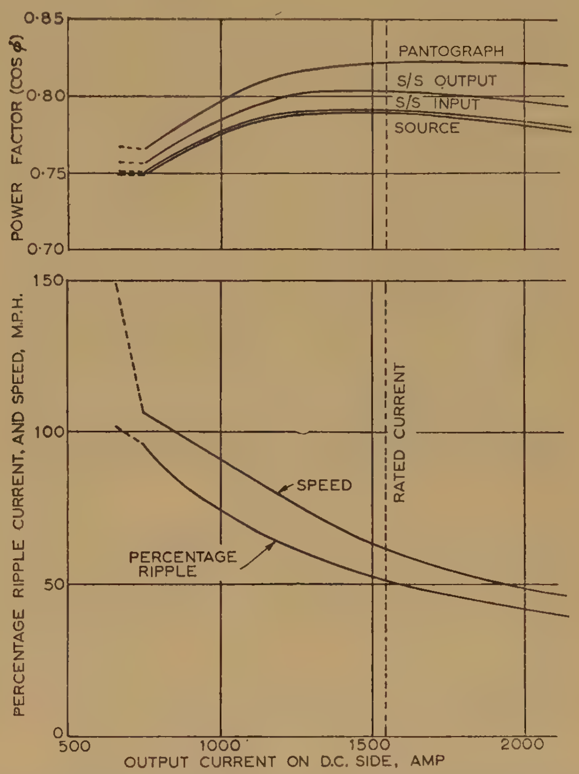

Fig. 10.—Power factor, locomotive speed and percentage ripple current in motor circuit plotted against d.c. output current for a 3 000 h.p. locomotive.

Two other values were chosen for the inductance of the d.c. reactor, including the infinite-inductance case, and the results are compared in Table 6 for the locomotive full-load condition. In the case of infinite inductance, the losses in the d.c. reactor have been taken as being the same as for the 7·3 mH case.

(4.1) The Effects of Increasing the Smoothing Inductance

The results given in Table 6 indicate that the main points in favour of using 7·3 mH instead of 2·05 mH are as follows:

(*a*) The r.m.s. value of the primary current is reduced for a given output current. This makes possible a reduction in the size of the rectifier transformer corresponding to a reduction in apparent-power rating of 7%.

(*b*) The power factor at the substation output to the contact wire is increased. At rated load the increase is from 0·80 to 0·86.

(*c*) The amount of ripple current supplied to the load is reduced, resulting in smaller losses and improved operating conditions for the traction motors. At rated load the reduction is from about 50% to about 20%.

There are the following disadvantages:

(*d*) The reactor has greater weight and size.

(*e*) The harmonic content of the primary current is increased.

(*f*) The motor back-e.m.f. is slightly reduced for a given output current; this is mainly due to the increased resistance of the reactor.

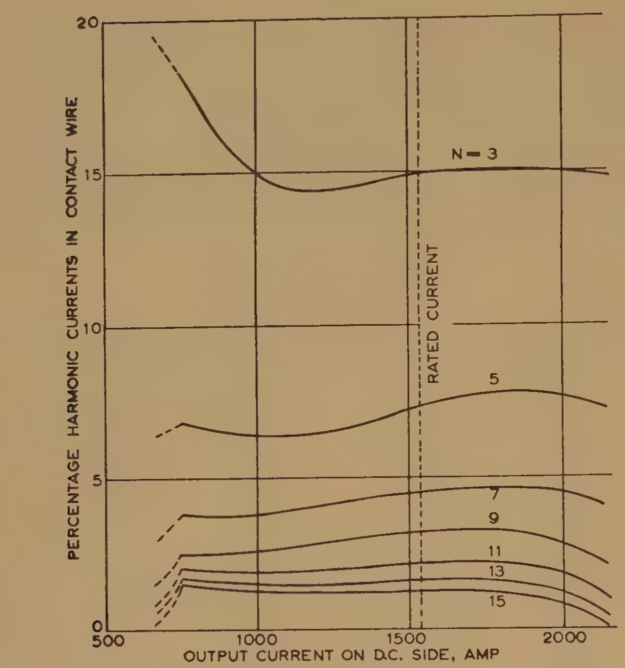

Fig. 11.—Harmonic currents in contact wire as percentages of the r.m.s. value of contact-wire current for a 3 000 h.p. locomotive.

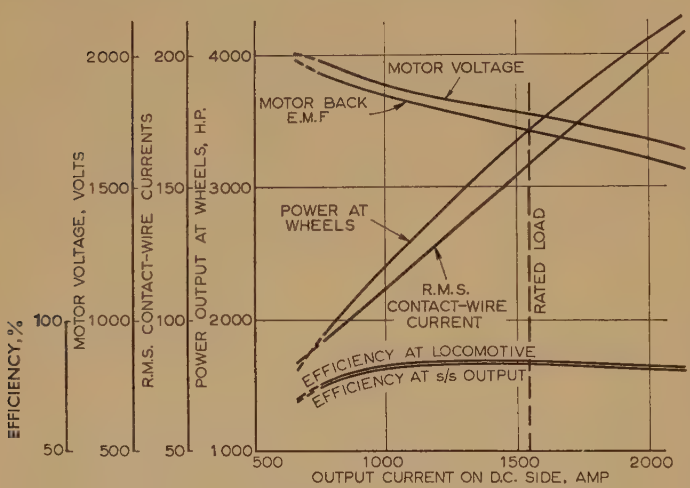

Fig. 12.—Efficiencies, power output at wheels, r.m.s. contact-wire current and motor voltage plotted against d.c. output current for a 3 000 h.p. locomotive.

(4.2) Typical Power Balance

The flow of power throughout this typical system is interesting, and provides a check on the digital computer calculations. The manner in which power flows is illustrated in Fig. 13. Power generated at the source is associated with the fundamental component of current lagging behind the supply e.m.f., such that its active component supplies the power output of the locomotive and all the losses, while its reactive component supplies the demand for reactive power. The fundamental power input to the locomotive, which is equal to the power generated at the source minus the fundamental current losses in the system from source to pantograph, is equal to the locomotive output plus the locomotive losses plus the harmonic losses in the system from source to pantograph. In other words, the locomotive takes fundamental power from the system, part of which is used by the motors; the remainder, minus the losses in the locomotive, is returned to the contact wire as harmonic power to supply the harmonic losses from the contact wire to the source. A typical example of the flow of power is given in Table 7, based on the locomotive data in the Appendix. Further details of performance for this case are included in Figs. 10, 11 and 12.

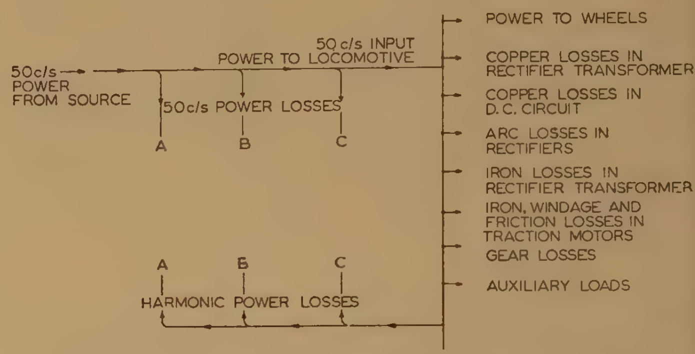

Fig. 13.—Power flow in rectifier locomotive and supply.
A. Supply system.
B. Substation.
C. Contact wire.

Table 6

COMPARISON OF RESULTS FOR A 3 000 H.P. LOCOMOTIVE FOR THREE VALUES OF D.C. REACTOR INDUCTANCE

	Inductance of series reactor, mH		
	2·05	7·3	Infinite
Inherent delay angle, degrees	8·4	2·8	0
Angle of overlap, degrees	23	35	37
Locomotive speed, m.p.h.	61	60	60
D.C. motor back-e.m.f. (two in series), volts	1 720	1 694	1 681
D.C. motor applied voltage (two in series), volts	1 775	1 747	1 738
Percentage motor ripple current	52%	20%	0%
Power output at wheels, h.p.	3 400	3 352	3 340
Efficency: Wheels/output from substation	83%	82%	84%
Efficiency: Wheels/input to pantograph	84%	84%	87%
Total r.m.s. contact-wire current, amp	158	146	142
3rd harmonic current in contact wire	14·8%	21·6%	26·4%
5th harmonic current in contact wire	7·4%	11·1%	13·2%
7th harmonic current in contact wire	4·5%	6·2%	7·0%
9th harmonic current in contact wire	3·2%	4·1%	3·7%
11th harmonic current in contact wire	2·2%	2·7%	2·0%
13th harmonic current in contact wire	1·6%	2·0%	1·4%
15th harmonic current in contact wire	1·3%	1·4%	1·2%
R.M.S. fundamental voltage at pantograph, kV	23·45	23·79	23·96
R.M.S. harmonic voltage at pantograph, kV	1·60	2·04	2·19
R.M.S. total voltage at pantograph, kV	23·54	23·88	24·07
Power factor at output from substation	0·80	0·86	0·90
Power factor at pantograph	0·82	0·88	0·92

Table 7

POWER BALANCE FOR A 3 000 H.P. LOCOMOTIVE AT APPROXIMATELY RATED LOAD

Electrical conditions	As Appendix	
Mean direct current, amp	$I_d = 1\,576$	
Alternating voltage at source, volts	$V_p = 25\,000$	
Inherent delay angle, degrees	$\alpha = 8{\cdot}4$	From Deuce result.
Angle of overlap, degrees	$\mu = 24{\cdot}0$	
Motor back-e.m.f., volts	$V_m = 1\,709$	
Fundamental component of contact-wire current, amp	$I_{1p} = 159$	
Fundamental phase angle (at source), degrees	$\gamma_{1p} = 37°48'$	
Total r.m.s. harmonic contact-wire current, amp	$I_{np} = 28{\cdot}8$	
Peak second-harmonic current, amp	$I_{2d\mu} = 797$	
Harmonic power loss—pantograph to source, kW	2	Summation of losses to give input.
Fundamental power loss—pantograph to source, kW	70	
Rectifier transformer primary–copper loss, kW	21	
Rectifier transformer secondary–copper loss, kW	27	
D.C. circuit copper loss (including series reactor), kW	130	
D.C. circuit copper loss (a.c. component), kW	49	
Rectifier arc losses, kW	63	
Rectifier transformer iron loss, kW	8	
Locomotive auxiliary losses, kW	88	
Total losses, kW	458	
Power output (air gap), $I_d \times V_m$, kW	2 693	
Total input at source, kW	3 151	
Power input from Deuce calculation $= 25 \times 159 \times \cos 37°48'$, kW	3 141	

(4.3) Power Factor

The results described in the previous Sections indicate that, for a typical locomotive operating at rated load, the power factor at the substation could be of the order of 0·8 (Fig. 10). This value of power factor is broadly in agreement with operating experience on the S.N.C.F.[2]

The conditions relevant to Fig. 10 may be pessimistic from the point of view of power factor for two reasons: line capacitance has been neglected and the smoothing inductance in the d.c. circuit is rather low (see Table 6). For a smoothing inductance of 4 mH the power factor at the substation output at rated load would be 0·83, the percentage ripple current then being 35%. This value of power factor will be further improved if allowance is made for line capacitance. Calculated and measured power factors for the motor-coaches on the Lancaster–Morecambe–Heysham system range from 0·85 to 0·89 (Table 5) at the substation output.

(4.4) Harmonic Loading of the Supply System

From the harmonic currents given in Fig. 11 and the system impedance given in the example in the Appendix, it can be shown that the total r.m.s. value of the harmonic voltage at the substation input is only 0·32% of the fundamental. This is for a single locomotive at rated load, and neglects system capacitance. Three trains loaded at once would therefore produce about 1·0% (excluding harmonic cancellation between trains).

These results are based on the neglect of the capacitances of the contact wire, supply system and any installed capacitors. Rectifiers are often regarded as harmonic-current generators. If this is so, the harmonic currents fed into the contact wire from the locomotive will not be greatly affected by the presence of capacitance, but many of the harmonic currents in the system will be increased. A more general digital computer programme[4] is being planned, which will permit a rigorous investigation of this problem.

(4.5) Several Trains on a System

The calculation of performance, as illustrated in the preceding Sections, relates to a single train fed through a typical traction supply network. However, this is only of interest to traction engineers if the results so obtained may be used to compute conditions with several trains operating on the system. Since the trains have a common impedance in the 3-phase supply network, substation transformer and some of the contact wire, any one train will produce voltage distortions which can affect the performance of other trains. In assessing the effects of interference between trains, the following factors should be taken into account:

(*a*) As shown in Table 6, at a given load wide variations of inherent delay angle and overlap produce very much the same power output at the wheels.

(*b*) From the power-factor curve in Fig. 10, it can be calculated that for a d.c. load variation of from 44% to 140%, the phase angle of fundamental current at the source varies only by about 3°.

(*c*) The r.m.s. harmonic voltage at the pantograph on full load is only 6·5% of the fundamental voltage, and since the impedance in the rectifier commutation circuit will be increased by a factor of three for the third harmonic, compared with the fundamental, then, as a rough approximation, the commutating current due to the voltage distortion will be only about 2% of that due to the fundamental voltage.

These points indicate that it should be sufficiently accurate for most purposes to calculate the effective supply impedance for one train, in the presence of others, by multiplying each section of impedance common to other trains by the ratio of the r.m.s. current in that section to the r.m.s. current taken by the train being considered, these values being preliminary estimates. Having calculated the effective supply impedance, the performance of the train can be calculated using the digital computer programme as for a single train problem.

(5) RECTIFIER OPERATING CONDITIONS

In the future development of rectifiers for use on locomotives and motor-coaches, it may be necessary for the designers to know the accurate waveshape of the reverse voltage applied to the rectifier during its non-conducting period, as well as that of the anode current.

The digital computer programme allows an accurate calculation of both these quantities to be made, an example being given in Fig. 14. From the rectifier designer's point of view, one of the most interesting times in the cycle is that immediately following the completion of commutation. The circuit natural-frequency oscillations at the end of anode current commutation can be evaluated by current-injection methods as used in circuit-breaker studies.

(6) FURTHER INVESTIGATIONS

Some of the problems which will need further examination have been mentioned in the paper; these include the effects of system capacitance and the operation of several trains on a system. The problems are, of course, extremely complex. It is intended to obtain solutions for a number of particular examples, so that approximate methods can be put to the test. A general approach to rectifier problems has been described elsewhere,[4] and will form the basis of a general rectifier programme for the digital computer.

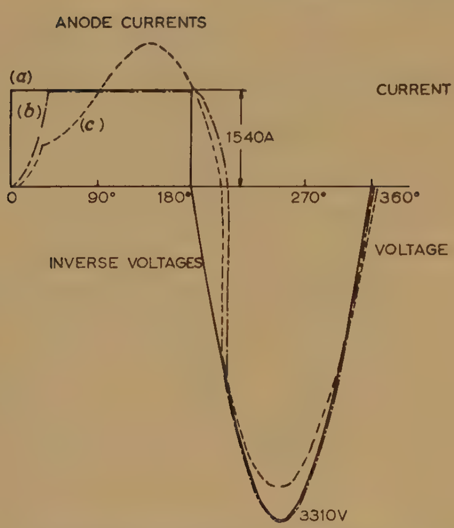

Fig. 14.—Anode currents and inverse voltages for a 3000 h.p. locomotive according to 'simple' and 'infinite inductance' theories and Deuce calculations.

(*a*) Simple infinite-inductance theory.
(*b*) Infinite-inductance theory.
(*c*) Deuce calculation.

(7) CONCLUSIONS

The paper has attempted to illustrate the imperfections in the accepted rectifier theory when dealing with single-phase rectifiers as applied to a.c. electric traction. Details of tests on the Lancaster–Morecambe–Heysham system have been given to illustrate the errors in the accepted theory, and these same tests used to justify the new approach. A specimen 3000 h.p. locomotive on a typical traction system was used to show some results of the theory. The traction performance of the locomotive in terms of voltage at the motors can be predicted with sufficient accuracy by accepted theory. A more detailed approach such as that given here is necessary to derive power factor, r.m.s. line current, line-current harmonics and ripple current in the motors. The need is discussed for further investigations; in particular into the effects of capacitance on the a.c. side.

The existing digital computer programme has been used to study fault conditions, a detailed account of which is outside the scope of the paper.

(8) ACKNOWLEDGMENTS

The tests on the Lancaster–Morecambe–Heysham section of British Railways were carried out with the co-operation of the British Transport Commission, whose foresight in planning this experimental system has made possible the practical verification of the calculations described in the paper.

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(10) APPENDIX

(10.1) Circuit Equations

An equivalent circuit for a bi-phase installation is shown in Fig. 15(*a*); this circuit can be derived directly from that in Fig. 2. The mesh equations in terms of anode currents $i_{\rm I}$ and $i_{\rm II}$ are:

$$\left.\begin{aligned}\sqrt{2}V_{so}\cos\omega t - v_d - v_{\rm I} &= (Z_e + Z_n)i_{\rm I} + Z_n i_{\rm II}\\ -\sqrt{(2)}V_{so}\cos\omega t - v_d - v_{\rm II} &= Z_n i_{\rm I} + (Z_e + Z_n)i_{\rm II}\end{aligned}\right\} \quad (30)$$

where

$i_{\rm I}$, $i_{\rm II}$ = Instantaneous value of the current in anode I or anode II, respectively.

$v_{\rm I}$, $v_{\rm II}$ = Instantaneous value of the anode-to-cathode voltage of element I or element II minus the arc-voltage drop, v_c, of a single element (bi-phase).

v_d = Effective back-e.m.f. in the d.c. circuit, plus the arc voltage drop v_c (bi-phase) or twice the arc voltage drop v_c (bridge).

i_d = Instantaneous value of the current in the d.c. circuit.

$$Z_e = R_e + L_e d/dt$$
$$Z_n = R_n + L_n d/dt$$

and

$$R_e = R_a + R_{ss} + 2k^2(R_{pp} + R_p) \quad . \quad . \quad . \quad (31)$$
$$R_n = R_d - k^2(R_{pp} + R_p) \quad . \quad . \quad . \quad . \quad . \quad (32)$$
$$L_e = (1/\omega)[X_a + 2k^2(X_{sc} + X_p)] \quad . \quad . \quad . \quad (33)$$
$$L_n = L_d - (k^2/\omega)[2X_{sc} - X'_{sc} + X_p] \quad . \quad . \quad (34)$$

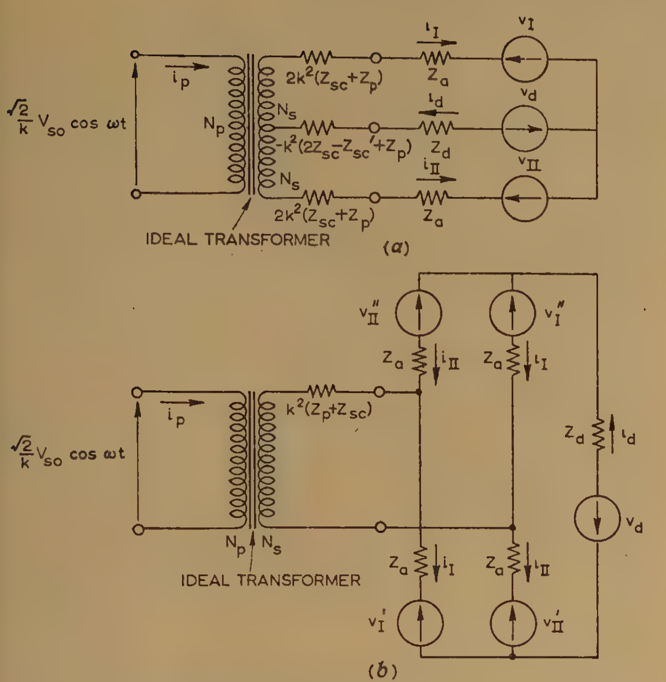


Fig. 15.—Equivalent circuits.
(a) Bi-phase.
(b) Bridge.

An equivalent circuit for a bridge installation, shown in Fig. 15(b), is derived from the circuit shown in Fig. 3. The mesh equations in terms of i_{I} and i_{II} are the same as eqn. (30) if the coefficients are defined as follows:

$$R_e = 2R_a + 2R_{ss} + 2k^2(R_{pp} + R_p) \quad . \quad . \quad . \quad (35)$$

$$R_n = R_d - k^2(R_{pp} + R_p) - R_{ss} \quad . \quad . \quad . \quad (36)$$

$$L_e = (1/\omega)[2X_a + 2k^2(X_{sc} + X_p)] \quad . \quad . \quad . \quad (37)$$

$$L_n = L_d - (k^2/\omega)(X_{sc} + X_p) \quad . \quad . \quad . \quad . \quad (38)$$

and

$$v_{\mathrm{I}} = v_{\mathrm{I}}^{\mathrm{I}} + v_{\mathrm{II}}^{\mathrm{II}}$$

$$v_{\mathrm{II}} = v_{\mathrm{II}}^{\mathrm{I}} + v_{\mathrm{I}}^{\mathrm{II}}$$

It can be shown that the percentage commutating reactance for both bi-phase and bridge circuits is given by:

$$x_{pc} = \frac{X_e I_{dr}}{2V_{so}} \times 100 \quad . \quad . \quad . \quad . \quad (39)$$

where I_{dr} is the rated value of the total direct current.

(10.2) Circuit Conditions for 3 000 h.p. Locomotive Example

Electrical Conditions.

The locomotive is on the maximum rectifier transformer tap on the 25 kV winding, and is delivering full load of 1 540 amp d.c. total.

132 kV 3-Phase Supply System.

Voltage at source = 132 kV
Short-circuit capacity = 2 000 MVA
Ratio of reactance to resistance = 4

The above conditions give the following quantities when referred to the 25 kV of the contact wire:

Reactance = X_{sup} = 0·606 ohm
Resistance = R_{sup} = 0·152 ohm

Substation Transformer.

Primary/secondary voltage at no-load = 132/25 kV
Rating = 15 MVA
Percentage reactance = 10%
Copper loss at full load = 110 kW
Iron loss = 40 kW
Magnetizing current = 1%

The above conditions give the following quantities when referred to 25 kV:

Reactance = X_{sub} = 4·167 ohms
Resistance = R_{sub} = 0·306 ohm

Contact Wire

Reactance = X_{con} = 7·60 ohms
Resistance = R_{con} = 2·31 ohms

Locomotive.

The simplified locomotive circuit as applying to the top tap comprises two bridge circuits, each feeding two traction motors in series, and each motor having a series reactor.

Equivalent direct current of two bridges at full load	= I_{dr}	= 1 540 amp
Total rectifier transformer voltage at no-load	= V_{so}	= 2 340 volts
Rectifier e.m.f.	= V_{do}	= 2 110 volts
Rectifier transformer turns ratio	= k	= 0·093 6
Percentage reactance of rectifier transformer (referred to primary apparent power at 1 540 amp d.c.)	= x_{sc}	= 7·7%
Reactance of rectifier transformer in ohms from x_{sc}	= X_{sc}	= 13·368 ohms
Resistance of rectifier transformer primary winding	= R_{pp}	= 0·800 ohm
Resistance of rectifier transformer secondary winding (total)	= R_{ss}	= 0·009 ohm
Rectifier transformer iron loss at 25 kV		= 8 kW
Rectifier transformer magnetizing current at 25 kV		= 2 amp
Inductance of d.c. reactor (per motor)	= L_{sr}	= 2·05 mH
Resistance of d.c. reactor (per motor)	= R_{sr}	= 0·017 7 ohm
Inductance of d.c. motor	= L_m	= 0·7 mH
Resistance of motor armature	= R_{ma}	= 0·017 1 ohm
Resistance of motor compoles	= R_{mi}	= 0·006 1 ohm
Resistance of motor series field	= R_{mf}	= 0·012 8 ohm
Resistance of motor series field divert	= R_{md}	= 0·113 5 ohm
Rectifier transformer tertiary loaded at 0·8 power factor and 75% load		= 88 kW

The parameters for the Deuce programme [see eqns. (35), (36), (37) and (38)] become:

$$R_e = 0{\cdot}080\,5 \text{ ohm}$$
$$R_n = 0{\cdot}114\,2 \text{ ohm}$$
$$\omega L_e = 0{\cdot}451\,0 \text{ ohm}$$
$$\omega L_n = 0{\cdot}638\,4 \text{ ohm}$$
$$(\sqrt{2})V_{so} = 3\,309 \text{ volts}$$

[The discussion on the above paper will be found overleaf.]

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE UTILIZATION SECTION, 14TH MARCH, 1957

Mr. E. L. E. Wheatcroft: As we have been reminded, the French Railways were the first to go in for standard-frequency electrification seriously, but they seem to have been slow to appreciate the merits of the rectifier locomotive. On the other hand, we in this country, having been slow starters with electrification, seem to have appreciated the rectifier locomotive from the beginning.

As a result there has recently been an intensive design effort going on with this type of locomotive, and everywhere in the country all sorts of groups have been studying the problems and most of them have, I think, been traversing the same line of thought. It is therefore very opportune that somebody should now set out the principal parameters involved. As the authors have said, this does not involve any new scientific principles but it does involve a good deal of new thought. For example, the standard book on rectifiers is now 25 years old, and the most recent book mentioned in the Bibliography came out 18 years ago; and, what is worse, by the time both these books were published the single-phase rectifier was thought to be out of date and hence nobody bothered to say much about it. These two groups of authors are the first to say they have not given us all the answers, but they have, I think, set out the problems in a very valuable way.

Paper No. 2340 U throws some light on the problem of voltage regulation of a transmission line supplying a single-phase rectifier load. It also gives the results of voltage drop as calculated by the so-called simple infinite-inductance method, by the rigorous Deuce method, and by test, showing that the test results lay between the simple theory and the more rigorous Deuce theory, but were nearer to the latter.

Why do we not stop bothering about this so-called simple infinite-inductance theory? It does not seem to have any merits, except for those who are limited to sixth-form mathematics. It has perhaps one further merit, that it is possible to present all the parameters on a single curve plotted against angle of overlap. I would think, however, that anyone with access to Deuce or a similar computer could work out the answers for all likely variations of inductance and resistance, on both the alternating- and the direct-current sides, and could present the solutions as a family of curves plotted for all time.

Even for those who do not have access to Deuce there are other methods, and I think a useful suggestion is that of setting up a model. The equivalent circuits given in the paper which were presented to Deuce do not require any more pieces of apparatus than actually lie in any university engineering laboratory, and I would have said that it is a simple and conveniently cheap way of finding all the answers one is likely to need.

Dr. J. C. Read: Referring to Paper No. 2339 U, I think the use of ignitrons for this duty has been dictated in some countries more by availability than by special suitability, as they have the limitation that the ignitor firing circuit cannot operate well over a wide range of supply voltage; also, air cooling seems preferable to water cooling for locomotive service.

In comparing bridge-connected single-anode rectifiers with single-way-connected multi-anode rectifiers for locomotives, it is not always true that the bridge connection is the better, as the savings in the transformer are offset—sometimes more than offset—by the increased cost, weight and complication of the rectifiers and their auxiliary excitation apparatus.

It is not my experience that semi-conductor rectifiers are not competitive in price at present. The semi-conductor vehicle is worth somewhat more than the mercury-arc type; and to the designer there are incidental factors that also help, e.g. the direct voltage no longer has to be chosen as a compromise between conflicting requirements. In fact, the British Transport Commission recently ordered 35 germanium-rectifier motor-coaches against competition by motor-coaches of the mercury-arc type.

Silicon rectifiers promise to bring advantages when reliable silicon cells are available in quantity and their application problems have been explored, but that stage has not yet been reached. For the present, the germanium rectifier has proved itself, by the trouble-free operation of the prototype on the Heysham line, to be already suitable for the immediate railway requirements in this country.

Regarding Paper No. 2340 U, the authors have explained their problem and how it can be solved, but have not given any general results. Such results can be expressed in general form, once and for all, in a few charts of curves, as functions of the inductive direct voltage drop and of the ratio of d.c. to a.c. inductance, with a simple correction for practical variations in the circuit resistance. Extreme accuracy would be pointless, since a locomotive or motor-coach operates under constantly changing conditions, not only as regards its current, but as regards the reactance and resistance of the a.c. supply to it. As at least three makers in this country already possess such data, I hope the authors will now make their results available, in simple general form, to the industry as a whole. Regarding power factor, I think they were right to use $\cos\phi$ and not the total power factor; but what method did they use in measuring $\cos\phi$?

Dr. W. G. Thompson: The computer enables an optimized design to be obtained where space is limited to that available on the vehicle.

Because a rectifier acts as a frequency convertor, each harmonic on the d.c. side is linked with a corresponding pair on the a.c. side. In the case of a rectifier locomotive, the second harmonic on the d.c. side is associated with the fundamental and the third harmonic on the a.c. side, and similarly for the sixth, fifth and seventh harmonics.

The real limitation of the infinite-inductance theory is that in making the d.c. impedance infinite the interaction between the a.c. and d.c. harmonics is discarded, whereas, in practice, it is known that any member of one of the groups of harmonics cannot be modified without influencing the associated pair. Fortunately the damping effect of the d.c. circuit reduces resonance effects on the a.c. side arising from the energy transfer. For this reason a relatively small cathode choke should be effective on the locomotive, notwithstanding bi-phase rectification. Fig. A shows the effect of successive partial elimination of a.c. harmonics up to the seventh, although it does not appear from practical results that such treatment is necessary.

Fig. B shows the results of tests carried out on a standard traction motor at 700 volts with loads of 50 amp and 200 amp derived from a bi-phase rectifier. The harmonic content of the alternating current was 17·1% of third, 7·9% of fifth and 4·7% of seventh.

The commutation of the motor itself was good, and heating tests showed that no revolutionary change in the design appeared to be necessary to make the motor entirely suitable for working on bi-phase rectified current.

Mr. S. B. Warder: In the interests of accuracy, I should like to put the Lancaster–Morecambe–Heysham line into its true relationship with the policy of the British Transport Commission during the last five years.

The decision to rehabilitate the line electrically was taken before the results of the Annecy experiments were known, and

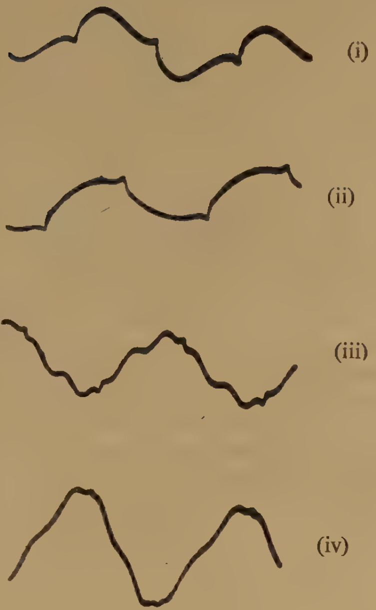
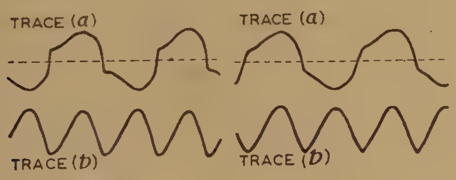


Fig. A.—Effect of partial elimination of harmonics.

(i) Without filters. (ii) Third harmonic filtered. (iii) Third and fifth harmonics filtered. (iv) Third, fifth and seventh harmonics filtered.



(i) (ii)

Fig. B.—700-volt d.c. traction motor supplied from bi-phase mercury-arc rectifier.

(i) 50 amp d.c. (ii) 200 amp d.c.
Trace (*a*), alternating current. Trace (*b*), armature current.

was facilitated by the opportunity to use standard d.c. sub-station equipment readily to hand. It was not engineered as a scientific testing ground from its inception. The substation multi-anode rectifiers and 1 500-volt motors were not the type of items which I would have thought were suitable for experimental purposes, and all the three trains were identically equipped.

This situation has since been remedied and in addition we have introduced a train with single-anode rectifiers, and a fourth train with equipment of another manufacturer will shortly be introduced for experimental trial.

The decision of the Commission to adopt the a.c. system as the future standard of British Railways has switched the centre of interest in respect of technical experimental testing to the two proving grounds of the Manchester–Crewe line and the Clacton–Colchester section of the Eastern Region, and that is where the main experimentation will take place.

I am making this point primarily to indicate that the conditions under which much of the information presented in the papers was obtained are entirely different from those which will apply in the future, and for this reason I find it rather difficult to accept any conclusions which may be drawn as a consequence as necessarily applicable to the system which will prevail in the future, where every feature will be entirely different from anything which has been used on the Lancaster–Morecambe–Heysham line, whether it be the supply system as a whole, the rolling stock or the fixed equipment.

A symposium of papers on the subject of rectifiers on locomotives was presented to the American Institute of Electrical Engineers very recently. Included was a paper covering present practices in Europe, and in commenting on the decision of the B.T.C. to adopt the single-phase 50 c/s system the authors came to the conclusion that the decision was made primarily in the interests of export trade. They reached that conclusion because the cost difference between the two systems was so marginal.

Now that is quite wrong. Export considerations played no part whatsoever in the decision which was reached: the decision was taken on the grounds that all the evidence indicated that it was the right one for British Railways. I mention this because a chance word out of context or a misinterpretation of the conditions can set up a chain reaction which can have far-reaching consequences when a vast change of a national character is prejudged before full information under exact service conditions is available to support it.

I am further conscious that the Post Office takes a very great interest in all that we are doing, particularly in what effects my arrangements will have on their telecommunications circuits, and likewise the Central Electricity Authority have important interests to protect. I have therefore to be very circumspect in what I do and say. So while much of this information is of the greatest value for those whose job it is to meet our requirements, I prefer to wait and see a little longer.

Dr. H. von Bertele: Irrespective of whether centre-point or bridge connection is used, the voltage ripple in the output of the single-phase rectifiers is some 67% over the average direct voltage. In a purely resistive circuit this would appear to introduce a pulsating current where peak-to-peak value is nearly $1\frac{1}{2}$ times that of the d.c. component. Ripple of such magnitude has a very adverse effect on the commutation and losses of a conventional commutator motor unless elaborate precautions are taken, and it is much cheaper to reduce the ripple by a reactor in series with the motor. However, from the aspect of locomotive weight it is important to select a reactor which gives the greatest smoothing for the smallest size, and for this one must determine the relationship between the motor and reactor ratings

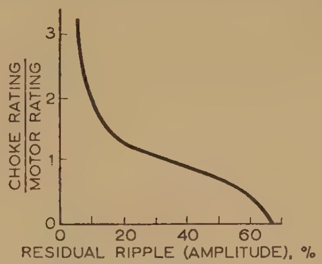


Fig. C.—Relative choke-rating requirements for ripple reduction when feeding traction motors from full-wave single-phase rectifiers.

in terms of the ripple in the motor circuit. Fig. C shows the equivalent transformer rating of a smoothing reactor, with respect to the d.c. output, for a single-phase full-wave rectifier feeding a purely resistive load. It is a peculiarity of this ratio that it does not follow the increase of inductance required for better smoothing, as shown in Fig. 19 of Paper No. 2339 U, for in the range 15–55% ripple the choke size rises less rapidly than the ripple decreases, because the iron losses decrease rapidly in this range. This, then, permits one to obtain a low percentage ripple with comparatively small reactors, and so to use traction motors of largely conventional design.

Fig. 16 of Paper No. 2339 U simplifies the auxiliary circuits

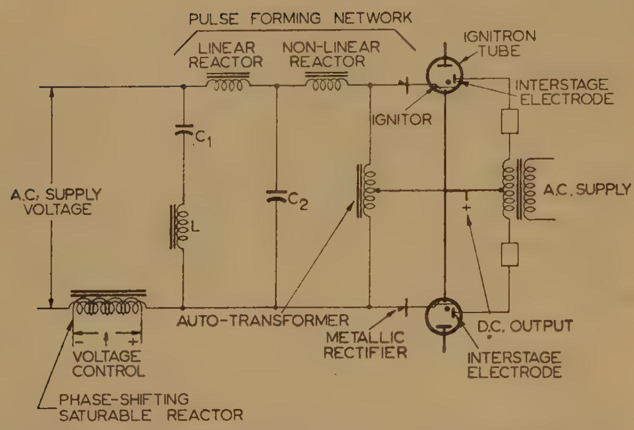


Fig. D.—Typical excitation circuit for a pair of ignitrons firing in 180° phase displacement.

associated with ignitrons, and from Fig. D it will be seen that, in practice, these circuits are marked by a number of inductors, capacitors, transductors and transformers. Most of this equipment is needed solely to produce the 200-volt 20 amp pulses required each cycle, timed to within 4–5 microsec of the firing instant. This additional weight and complication is one of the reasons for the present trend towards the use of excitrons on rectifier locomotives, for here the excitation requirements, being steady, are far less exacting.

One of the problems inseparable from the use of mercury-arc rectifiers on moving vehicles is the splashing of the mercury itself, and rectifiers for such duty must accommodate various devices to prevent this splashing causing short-circuits to other electrodes; moreover, it causes instabilities in the vapour content and distribution, and thus concomitant instabilities in firing performance and voltage-withstanding capacity. However, many of these problems can be overcome, and a considerable reduction effected in the weight of mercury required, by the use of the single-anode Nevitron,* while more recent developments have shown that, by suitable control of the emission zone, the mercury content may be reduced to a thin film on a metallic cathode. Fig. E shows a simplified cross-section of such a valve, designed for an output of 600 amp.

* von Bertele, H.: 'Cathode-Spot Behaviour and the Thermal Control of the Emission Zone in Mercury-Arc Rectifiers', *Proceedings I.E.E.*, Paper No. 1616 S, March, 1954 (101, Part II, p. 493).

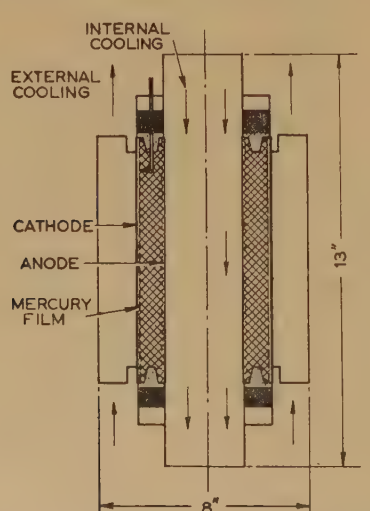


Fig. E.—Cross-section through 600 amp film-cathode rectifier.

Mr. J. A. Broughall: With reference to Paper No. 2339 U, I should like to remark that the railway traction engineer is not a free agent to have a locomotive of any weight he would like: he is restricted by rather severe parameters. The axle load must not exceed so much, the cost of the locomotive—both its first cost and its maintenance cost—is affected by the number of wheels, and he can only go from one whole number of wheels to another, normally from four to six axles. Commercial considerations decide that trains are needed to travel at 100 m.p.h. and to go from one place to another, in spite of speed restrictions, in round numbers of hours. I am very much in favour of this but it does mean that the railway cannot treat every pound and every ton as of equal value as the authors tend to do. For example, if one exceeds 20 tons per axle it is impossible to run over most lines at all.

Harmonics do exist, of course, but notwithstanding the very weak supply of the Lancaster–Morecambe–Heysham line the disturbance to the supply system because of these harmonics, the power factor and the unbalanced load is very slight. It will become much less on the larger systems now under consideration.

It is one of the mysterious workings of Providence that when we need a tool it comes, and how these problems would be tackled without the electronic computer I really do not know. But I do think that the people working on this must be thorough; they must include all the variables and look for instantaneous as well as average values, because the performance of machinery depends upon what happens in a fraction of a second. I think most of the values in the papers are average values for seconds and minutes. They are useful but they are not the whole story. Moreover, the circuits must not be over-simplified or misleading conclusions will be drawn, particularly now that the computer seems to be able to calculate everything.

Mr. J. C. Turrall: I shall confine my remarks to Paper No. 2339 U, which covers the ground which many traction engineers have been exploring for the last two years. The tendency has been in recent years to stress the advantages of rectifier equipments in enabling higher adhesions to be worked to. This is an admirable feature but it is common to all systems whereby motors can be permanently connected in parallel and have voltage control, but with a large number of motors such as are used on a locomotive or a multiple of units as used in motor-coach stock the main traction essential is to share the load as evenly as possible over the motors and to be able to start the trains without an excessive number of starting steps and complex control gear. The well-proved series characteristic is still required, and a limit has to be set on the flatness of the motor curves: otherwise we find two motors, one running on half-load and the other running on 100% overload, flatness being defined as a small change in speed causing a large change in tractive effort. This problem is mentioned in the paper but I do not think it is emphasized sufficiently.

Regarding Fig. 1(*b*) in Paper No. 2339 U, I think it is better to regard the two motors in parallel as having a restraining effect on each other, a voltage rise on a slipping motor being impossible without the same rise taking place on the non-slipping motor, rather than the effect being due to the current being transferred through the equalizer connection, as stated in the paper.

With regard to the transformer tappings, the scheme shown in Fig. 6(*b*) requires twice as many transformer tappings as that in Fig. 6(*a*) for the same number of effective notches, and the 3-wire bridge circuit using the same number of contacts as the simple bridge circuit does not give exactly the same effect at the draw-bar as when equal tap changes take place on both arms of the circuit.

Regarding the transformer, the authors mention transformer

cores operating at flux densities near to saturation, and a figure of $B_{max} = 18\,000$ gauss is quoted. Does this figure indicate the actual flux density in the core when operating at nominal system voltage? If so, could the authors give the figures for the percentage increase in magnetizing current and losses when operating on 27 kV, and have any measurements of switching currents been made under these conditions?

Mr. F. C. E. Smith: The high-voltage circuit-breaker is the only item of protective equipment mentioned in Paper No. 2339 U. Do the authors intend to rely entirely on this circuit-breaker to clear all faults, including those in the traction-motor circuits?

A very good case for grid control as a means of starting a train from rest is given in Section 3.3.2.2. This method has the great advantage that it provides a steady control of accelerating current during the period when it is difficult to obtain smooth notching with transformer tappings owing to the asymptotic form of the motor characteristic at low voltage. A grid provided for this purpose can also be used to block fault currents in the traction-motor circuits, and I should like to ask the authors whether they have tried this.

Low-voltage tap-changing is more practicable on rectifier locomotives than it is on a.c. commutator-motor locomotives, owing to the higher design voltage of d.c. motors. If l.v. tap-changing is adopted the current-breaking contacts become available for clearing rectifier faults, and therefore special motor contactors may not be required.

High-voltage tap-changing equipment has, however, received much development on the Continent for a.c. commutator-motor locomotives. The design shown in Fig. 14 is a very good one for maintenance because there are only three oil-tight seals external to the transformer tank, and only two load-breaking switches. The circuit diagram for the l.v. tap-changer shown in Fig. 15 will, however, require a construction having an oil-tight seal and a current-breaking contactor for each tap. It is suggested, therefore, that l.v. tap-changing equipment must be designed with selector contactors mounted in an oil-filled casing on the side of the transformer tank if its maintenance cost is to be comparable with the high-voltage type developed on the Continent.

Mr. W. R. E. Taylor: I was interested to note the authors' comments on bridge connection and the apparent reduction in size of the rectifier transformer, but one must not overlook the fact that the transformer has to overcome twice the rectifier forward voltage drop when using this connection and thus the mean-apparent-power ratio for bridge connection and bi-phase is not as great as the authors' figures suggest.

The use of grid control for starting trains has big possibilities, but it may well present a problem to the rectifier designer, since the starting current (say 150% of full load current) will be required at maximum delay angle. It is estimated that with an anode voltage 25% of its maximum value, starting current 150% of full load current, overlap 28°, the rectifier will have to be derated to 72% of its free firing output if it is required to use phase-angle control to give 10% of the maximum d.c. output voltage.

The additional weight for larger rectifiers, grid-control gear, extra smoothing apparatus and added maintenance problems must be offset by the reduction in weight for omission of one or two steps in the on-load tap-gear arrangements.

The figures regarding values of ripple current are most useful; they approximate to the values obtained in the 3-phase half-wave connection using a purely resistive load without smoothing, and I think this can be taken as evidence that we pay too much attention to the reduction of ripple currents in rectifier output circuits.

The question of weight reduction is all important, and I would like to ask the authors whether aluminium windings have been considered, with perhaps Class H insulation.

No mention has been made of fire risk, and perhaps the authors can indicate if an Askarel-filled transformer is practicable from a weight point of view. It would seem that an aluminium-wound transformer with class H insulation and Askarel fluid has possibilities for this application.

[The authors' replies to the above discussion will be found on page 373.]

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 10TH APRIL, 1957*

Mr. F. Whyman: Having gone deeply into the first principles and literature on the subject and done a lot of independent thinking, the authors give the pros and cons of various constructions but do not in general indicate any preferences, which I think is a pity.

It is true that for many years the French railways largely avoided the use of rectifier-fed traction motors, relying more on 50 c/s a.c. commutation motors and motor-generator and phase-convertor systems. It may not be generally realized that this was mainly influenced by the fact that the development of mercury-arc rectifiers in France was many years behind that in Britain, the United States and Switzerland.

Sections 4.4.4 and 3.1.3 deal with non-inductive field shunting of the traction motors in rather contradictory ways. As indicated in Section 4.4.4, permanent non-inductive shunts to reduce flux ripple are generally accepted as beneficial and standard, but Section 3.1.3 warns against too much non-inductive shunting for field control owing to current surges arising from line voltage changes. I think the conditions are so different from direct-current traction that no real danger will arise with a.c. rectifier traction.

With a.c. traction, voltage rises due to other locomotives switching off power only appear as a mild voltage step without severe transients, and the necessarily high locomotive-transformer reactance and the smoothing choke in series with the traction motors will generally ensure only a modest rate of increase of current, with a small current overswing gently settling down to an increased new stable current value.

With direct-current traction, when a neighbouring locomotive suddenly trips off power for any reason, both being remote from a substation, the voltage transient sustained by the other locomotive can be severe, since all the current rejected must find a new path locally until the magnetic energy stored in the overhead-wire system has been dissipated.

It is not generally appreciated how important is this factor in easing conditions for rectifier-fed traction motors on alternating-current systems.

Paragraph 4 of Section 4.4.4 appears wrong, because with a reducing field diverter resistance the motor field must progressively be wound with more turns, and as for constant flux the field copper loss will remain constant, the field resistance must increase in greater proportion than the field current decreases. The field voltage therefore rises and the diverter current rises. Therefore the diverter loss, the product of two increasing quantities, progressively increases more than linearly with percentage divert, as follows:

Percentage of motor current diverted	5	10	20	50
Power lost in diverter as a percentage of field copper loss	5	11	25	100

* This refers to the paper by Messrs. Calverley, Jarvis and Williams only.

The heavy losses in permanent field-diverter resistances, smoothing chokes and high-loss transformers (referred to in Section 4.1.1) are some of the main reasons for the present low efficiency of rectifier locomotives, resulting in energy consumptions for equal duties generally higher than the traditional direct-current systems where much lower conversion losses are possible.

With reference to Section 4.3.2, the reasons given and others convince me that germanium semi-conductor rectifiers will not have a wide application in the power circuits of electric rolling-stock. The position is quite different, however, with silicon rectifiers, which appear eminently suitable by virtue of their high safe operating temperature and reduced hole-storage effect.

Mr. J. K. Lord: Little is said of semi-conductor rectifiers, e.g. germanium, which have distinct advantages over the mercury-arc types, and the paper would have been more complete with a comment on the relative merits of rectifier types, particularly as germanium is a recent discovery in respect of this application.

Tap-changing suffers from the disadvantage of a stepped form of control, and unless a large number of tappings are used the control is merely a series of jerks as the motors are notched up. If a large number of taps are provided there is increased maintenance, together with added initial cost, to provide smooth control. Could not some form of induction-regulator device be incorporated to smooth out the steps between intermediate tapping points, which would automatically reduce the current to the next higher tap. This would cut down the number of steps to a minimum and at the same time give completely smooth control: it would, of course, incur extra cost, which would need consideration. This point is mentioned in Section 3.3.2 but is not fully examined. Has anything been done in this respect? The discussion in Section 3.3.2.1 on this point is again not fully treated, and there appears to be scope for the use of a type of induction regulator which would span between adjacent voltage taps.

Electrical braking is only hinted at, whereas this method of braking, apart from being economical in power consumption, has also the distinct advantage in the saving in mechanical wear and tear of the locomotive as well as being a smoother brake.

Mr. W. H. Stonelake: Compared with Diesel-electric locomotives, which took about 20 years to reach their present practical form, the problem facing the designers of Diesel locomotives has been essentially one of determining the apparatus and circuits in order to match the known characteristics of the engine, the generator and the traction motors to obtain the best combination to suit traction requirements. Now the problem on rectifier locomotives consists of matching the transformer, the rectifiers and the traction motors. The fact that so much has been done in such a relatively short time is commendable.

In Section 4.2.3.2 the authors state that one of the advantages of the fully electrical scheme of tap-changing is that when the driver cuts off power, the unit switches instantly fall into the 'off' position, without repeatedly making and breaking circulating current. Whilst this is true, and is an advantage on rectifier-type motor-coach equipment, it should be noted that this method of cutting off power is not to be recommended as a regular procedure on locomotives, particularly when hauling long, loosely-coupled trains of unbraked goods wagons; in such a case, the sudden cutting-off of power may cause snatch in couplings, and a more gentle method of gradually reducing tractive effort is preferable.

In Section 3.3.2.2, the authors rightly draw attention to the advantages of using grid control of mercury-arc rectifiers as a means of obtaining smooth control of output voltage over the early part of the voltage range. This method could be used in conjunction with the l.v. control, using buck-boost as shown in the diagram in Fig. 12(*b*). The possibility of using grid control in this way might be put forward as an argument for recommending the l.v. buck-boost scheme.

Mr. H. Diggle: Although it is not easy to detect in the paper, and particularly in the conclusions, any special preferences of the authors for any of the alternative pieces of equipment, I gather that they consider shell-type transformers and l.v. tap-changing to be preferable to core-type transformers and h.v. tap-changing.

The shell-type versus core-type controversy is a very old one and hardly worth pursuing as far as transformers of the order of 3000 kVA are concerned. Equally reliable transformers can be made of either type.

After long experience of high-voltage tap-changers, and from examination of some of the newer Continental locomotives, I consider that h.v. tap-changing has many advantages, particularly if resistance transition is used. On a 3000 kVA transformer it presents no difficulty when one considers that h.v. tap-changing is performed at very high voltages on substation transformers up to 150 MVA. With h.v. tap-changing on a circuit of the type shown in Fig. 14, quite light currents are involved, and all the contact burning is restricted to two easily accessible air-break contactors on which the contact tips can easily be replaced, so that maintenance is much reduced. One design of h.v. tap-changer can be applied to all sizes of locomotives.

A dubious advantage (*d*), in Section 3.3.1.2, is claimed for l.v. tap-changing, namely that the selector contacts are more readily accessible. They have to be, as they will all get burnt and need replacement. With h.v. tap-changing the selectors can be left for long periods, as they never break current.

The paper conveys the impression that the size of transformer frame required for h.v. tap-changing (Fig. 7) must be greater than that for l.v. tap-changing where only one transformer core is involved. This is not necessarily the case. Considerable economy in frame rating (kVA) is possible by using the buck-boost principle, by making the rectifier transformer for 50% voltage only (i.e. halving the apparent power) and having a further winding for 50% of the rectifier voltage on the same core as the auto-transformer. By the use of a reversing switch, the windings can be in opposition or series to give zero (50 — 50) or 100% (50 + 50), and studies made for the bridge circuit [Fig. 5(*a*)] show that the relative frame ratings involved are 1·32 for l.v. taps only, and 1·33 for h.v. taps with buck-boost windings, so that the advantage of the former disappears.

H.V. tap-changing appears, therefore, to be the correct solution for locomotives, and this seems to be borne out by recent developments on the Continent.

Mr. G. R. Higgs: The paper does not deal with the important subject of auxiliary drives. This is a wide field and no very definite scheme appears to have emerged so far; fashions, mainly from Paris, seem to change from time to time. The requirements of the machines to be driven by the auxiliary motors are diverse, ranging from the constant-torque requirements of compressors and exhausters to the variable torque of fans and pumps.

Reference has been made to the claims of French railway engineers that they get 60% more adhesion with their a.c. rectifier locomotives than with d.c. locomotives. I think it should be realized that very great pains have been taken to achieve good adhesion results with the a.c. locomotives and that the same efforts have not been applied to the d.c. locomotives, and that improvements are attributable not only to the electrical parts of the locomotive but to the rather special design of the mechanical parts.

From the Section 3.3.1.4 on tap-changing impedance it might be inferred that the d.c. resistance drop is greater with bi-phase than with bridge circuits. It is, however, made clearer elsewhere in the paper that for equal percentage impedance in the trans-

formers the d.c. voltage drop is the same for each of these connections. It should, however, be realized that even though a larger circulating current will occur with the bi-phase circuit, the winding rating and the switches associated with it are also larger.

Mr. J. P. McBreen: I agree with the authors that there is plenty of scope for development in this application, especially as regards the rectifiers. These must be light, compact, able to withstand vibration and shock during operation and be capable of supplying a peaky load under widely differing supply voltage and cooling conditions. There is no doubt that mercury-arc rectifiers can be, and have been, designed for this duty, but surely the authors are wrong in advocating water cooling for these. For substation equipments, with the possible exception of a few replacement units, only air-cooled rectifiers have been supplied in this country for the past 15–20 years and it seems a retrograde step to re-introduce water cooling on rolling stock. When the complete equipment is taken into account I doubt if water cooling shows any advantage in weight or size over air cooling, and water cooling has a lot of obvious disadvantages. Incidentally, what is the maximum rating of the single-anode pumpless water-cooled rectifier available, and is there any restriction on size because of the water cooling?

Referring to Section 3.3.2.2, the use of grid control for this application would be an unnecessary complication for the slight advantage to be gained. On-load tap-changing will give all the voltage control necessary.

Mr. E. Hanson: On the choice of mercury-arc rectifiers, the authors do not, in fact, state any preference for water-cooled ignitrons, saying no more than that they have been used almost exclusively and have given good results. I assume that in the United States and in France it has been a case of using rectifiers which were readily available.

Blowers are usually present in any case for main motor cooling on locomotives, and for starting from cold it should be possible to heat up an air-cooled rectifier appreciably quicker than a water-cooled rectifier, since direct radiant heat can be used for the former.

For an application of such importance as this I consider it would be worth while to develop an air-cooled rectifier of larger size, specially designed for locomotive duty. An air-cooled pumpless single-anode rectifier has been developed in Switzerland for traction service which dwarfs anything yet seen in this country. Its rating when used in a mine locomotive is quoted as 1·6 kA at 960 volts. I would like to hear what are the authors' views on the possibilities of such development.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. H. B. Calverley, E. A. K. Jarvis, E. Williams, T. E. Calverley and **D. G. Taylor** (*in reply*): In the authors' view, strong and conclusive argments do not exist as regards many of the choices the designer of the equipment must make. Different engineers may consider different criteria to be the governing ones, e.g. the least maintenance equipment may not be the cheapest, or the lightest may not be the smallest. Many of the pros and cons are given in the papers, and where a contributor merely gives an opinion the authors will make no further comment.

Referring to Paper No. 2340 U, Mr. Wheatcroft mentions the possibility of expressing results in graphical form. If the basic equations are expressed as dimensionless quantities, there remain four parameters which can be specified independently, thereby precluding the possibility of presenting completely general results in a convenient form. Dr. Read suggests, in this context, that curves can be drawn on a restricted basis with corrections for resistance being made separately. The calculations and test results obtained from the Lancaster–Morecambe–Heysham system indicated the importance of taking proper account of resistance in the calculations described. Earlier attempts to modify calculations for variations in resistance failed, particularly with regard to power factor. In a particular example, calculations with resistance neglected yielded a power factor at the train of 0·79; the corresponding value taking proper account of resistance, in particular the motor diverter resistance, was 0·87 (see Table 4, Paper No. 2340 U).

A model circuit, as suggested by Mr. Wheatcroft, would provide useful information in the form of meter readings and waveforms; the task of analysing the waveforms into harmonic components would remain.

The authors feel that the infinite-inductance theory still has a part to play in the calculation of the regulation characteristics, so far as these affect train performance. A more rigorous approach becomes necessary when quantities such as harmonic currents in the line and motors, and power factor are required.

We agree with Dr. Read that $\cos\phi$ is the important quantity to consider; the difference between total power factor and $\cos\phi$ is not great, however, the distortion factor approaching 0·99 in typical cases (column B, Table 4, Paper No. 2340 U).

With regard to the measurement of $\cos\phi$, oscillographic records were analysed into harmonic components, utilizing a Deuce programme. The substation output voltage and current were recorded on the same film (see Fig. 7, Paper No. 2340 U), so that their fundamental components with respect to the same datum provided the information for calculating $\cos\phi$. Power factor at the train was estimated in a similar manner.

Dr. Read draws attention to the B.T.C. having ordered what is in fact a small proportion of germanium equipments in a predominantly mercury-arc programme. He implies that the extra first cost is compensated for by other factors but does not name them. The usual claim of higher efficiency for germanium is not justified at the direct voltages used for the motors on rectifier vehicles. The authors agree with Mr. Whyman that any real benefits will come from the use of silicon rectifiers—in the fairly near future. Dr. Read mentions the firing circuits for ignitrons, which do admittedly have to be designed for wide variations in supply voltage, but so also do all the other control gear and the auxiliaries on the locomotive. Tests show that a supply voltage drop to less than 60% reduces igniter pulse by only 17%.

In reply to Dr. Read, air cooling is admittedly simpler than water cooling, but the total volume of rectifier equipment is greater if air cooled—and in a locomotive greater volume means greater weight of mechanical parts, which can be a serious handicap.

Mr. Warder mentions that the Lancaster–Morecambe–Heysham line was not conceived as a scientific testing ground. Notwithstanding this fact, thorough testing was carried out to obtain confirmation of the correctness of the theoretical calculations presented in Paper 2340 U. In reply to Mr. Broughall, who warns against over-simplification of the circuits used in this analysis, we would comment that changes in magnitude of the parameters considered in Paper No. 2340 U will not affect the basis of the calculations. There remains a possibility, however, that factors which were justifiably neglected may assume importance in larger installations. One such factor is capacitance, whose probable effects are discussed in the paper. A programme taking capacitance into account is now available.

Fig. C differs from Fig. 19 of Paper No. 2339 U because Dr. von Bertele's calculations of the series reactor are based on

the case of a resistive load. The pulsating direct current flowing in the motor series field winding causes pulsations in flux, and the rotation of the armature in this flux results in armature voltages which have a component in phase with the ripple current: to this extent the load appears as a resistance. However, the authors believe this effect to be small compared with the inductive reactance of the circuit, and hence the values plotted in Fig. 19 are based on the assumption that harmonic currents are limited only by the reactance of the motor and series reactor combined. Dr. von Bertele also mentions the simpler circuits of the excitron, compared with the ignitron, but Fig. D for the ignitron should omit the phase-shifting saturable reactor and L and C to give a true picture. Regarding mercury splash, it is interesting that rectifier constructions exactly as used in normal substation rectifiers have been found to be perfectly satisfactory on trains.

Mr. Turrall's remarks are very apt; however, the intention was to regard condition (iii) of Fig. 6(*b*) as a running notch equivalent to condition (iii) of Fig. 6(*a*). By this means the number of tappings is the same in the two cases for a given number of notches. Regarding the 3-wire bridge circuit utilizing tap-changing alternately on the two halves of the winding, it will be understood that each motor delivers equal mean tractive effort whether the notch is a symmetrical or an unsymmetrical one. Regarding flux densities in transformer cores, we would say that a value somewhat above 18 000 gauss could be used at maximum line voltage. A peak switching-in current of approximately 250% of rated current has been obtained during tests.

Mr. Smith asks about high-voltage circuit-breakers. We consider that, having installed a high-duty high-speed circuit-breaker which on operation could clear any type of fault, it is desirable to use the circuit-breaker for all high-power fault clearing. Where the rectifiers are fitted with control grids there is some justification for using grid blocking, in addition to tripping the h.v. circuit-breaker in case of l.v. faults. Grid blocking has been used on the Lancaster–Morecambe–Heysham line for clearing l.v. faults, as well as for normal switching-off of the traction-motor current.

Mr. Smith's suggestion of an l.v. tap-changer with selector contacts in an oil-filled container is interesting. One doubts, however, whether the elimination of oil-tight seals is a justifiable reason for such a step. Section 4.2.3.3 explains that it is not necessary to use current-breaking contactors for each tap of an l.v. scheme.

Concerning the rating of rectifiers under grid-control conditions, tests carried out on single-anode air-cooled rectifiers and on water-cooled ignitrons have shown that no de-rating is required for operation under grid-control conditions, as cited by Mr. W. R. E. Taylor. Whether the complication introduced by the provision of grid control is worth while is open to question.

The use of aluminium windings for transformers would reduce the transformer weight by 5–10%, but the size and losses would be increased. The use of Askarel fluid, if operated at the same temperature as normally used for transformer oil, would increase the weight of the transformer by about 15%. If the cooling fluid (whether Askarel or any other liquid or gaseous medium) is suitable for appreciably higher temperatures, its use with Class H insulation would merit investigation to find if an overall advantage is realized after taking into account both the transformer itself and the cooling apparatus.

Mr. Whyman makes the point that d.c. locomotives cause much more severe transient voltages both in the motors and in the overhead line when switching off power. In fact, it is usual on rectifier locomotives on the S.N.C.F. to switch off by steadily notching back to the 'off' position, the d.c. circuit never actually being broken. The rectifiers form a discharge path for inductive energy stored in the d.c. circuit in the case of power interruption on the a.c. side. Mr. Whyman's figures for power losses in the field diverter include only those due to the d.c. component of the diverter current, but the statement made in Section 4.4.4 of Paper No. 2339 U includes also the losses due to ripple current which flows in the diverter. These decrease as the percentage of direct current diverted is increased, and so, in conjunction with the rising d.c. losses, will result in a minimum value of diverter loss at one ohmic value of the diverter.

On Mr. Lord's first comment we can only repeat our opinion that the germanium rectifier at present is expensive and shows little or no technical advantage over the mercury-arc type, but the situation will be quite different with silicon rectifiers. We agree with Mr. Lord's comments on infinitely smooth control and can only say that little has been done in this direction as yet. Any form of induction regulator device would have to be suitable in weight, cost, maintenance and speed of response.

Mr. Diggle strongly favours h.v. control and quotes several reasons. However, it should not be assumed that two of the advantages he claims, namely use of resistance switching and restriction of arcing duty to a very few load switches, cannot be applied with similar advantage to l.v. control schemes. The h.v. scheme using the buck-boost principle is interesting, as it does have some advantages while using a transformer little larger than for l.v. tap-changing. We find that for single-supply-voltage equipments the total winding apparent power is 19% greater than for the l.v. scheme. A buck-boost scheme with h.v. control rather similar to that mentioned by Mr. Diggle has been used in the Turkish Railway a.c. motor locomotives.,

In reply to Mr. Higgs, we confirm that the comments in Section 3.3.1.4 mean that to produce a given drop in direct voltage the ohmic value chosen for the tap-changing impedance is less if it is resistive than if it is reactive. Hence, to some extent, the advantage to the contactors which interrupt this current of a better power factor with a resistor is offset by the current being greater, particularly for a bi-phase circuit.

Mr. McBreen and Mr. Hanson ask what sizes of water-cooled ignitrons are available. The usual size is 8 in diameter, giving about 800 amp continuous rating per pair of tanks and substantial overload capacity in addition. Eight such tanks suffice for over

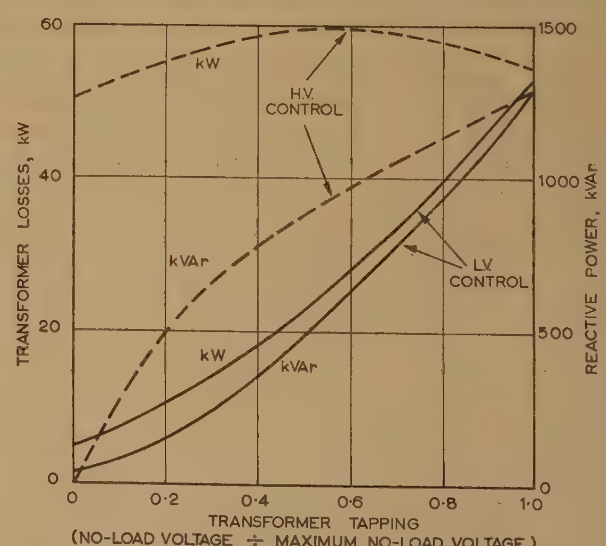


Fig. F.—Transformer performance, h.v. and l.v. control.

Conditions:

(i) Rated motor current.
(ii) Reactance of auto-transformer for h.v. control neglected.
(iii) Identical rectifier transformer for h.v. and l.v. control.
(iv) Transformer designed for single supply voltage only.
(v) Percentage reactance referred to actual apparent power, proportional to output voltage in l.v. case.

3 000 h.p. One might consider that more tanks would cause undesirable multiplication of auxiliaries and that fewer would disturb the circuits unduly in a bridge circuit if one tank had to be cut out of circuit. Larger ignitrons are used in the locomotives of the Virginian Railway, where 12 tubes of 12 in diameter suffice for the 6 800 h.p.

Fig. F shows reactive-power requirements and losses plotted against the ratio of actual output voltage to maximum output voltage for a typical 3 000 h.p. locomotive. This diagram amplifies the remarks in Section 3.3.1.2 of Paper No. 2339 U by showing that if, for example, a locomotive actually runs for most of its life at a notch corresponding to 70% of top notch voltage, then a simple h.v. control equipment has approximately 25 kW more loss and 270 kVAr more than the equipment with l.v. control. On the other hand, the no-load loss and reactive power are less for h.v. control than for l.v. control.

DISCUSSION ON 'FLAT PRESSURE CABLE'*

Before the WESTERN CENTRE *at* CARDIFF, 14*th January, and the* SOUTHERN CENTRE *at* SOUTHAMPTON, 27*th March*, 1957.

Mr. J. F. Wright (*at Cardiff*): In Section 3.2.1 the maximum stress for a 33 kV cable is given as 75 kV/cm, which appears rather low. Would this figure apply for a 33 kV cable made now?

The value of P_{min} is given in Section 3.3.3 as 7 lb/in^2, and it is claimed that this value is chosen so that the dielectric will always remain fully impregnated. Will this be so irrespective of dielectric thickness?

Mr. G. H. Bowden (*at Cardiff*): Why have ferrous metals been so carefully avoided in the reinforcement and protection of the flat pressure cable? Is it because trials of steel-wire reinforcement have shown that sheath and armour losses become abnormally high?

Transposition of cores is generally avoided when jointing the higher-voltage cables. To what extent, in practice, is transposition desirable in the flat pressure cable?

On systems where prospective fault currents are high, inter-core electromagnetic forces would seem likely to cause indentation on the bronze strips which lap the lead sheath at the points where circumferential wires pass over the round sides of the flat cable. Does the use of this cable place any limitation on fault currents to prevent this happening?

In the event of an unsymmetrical fault—as, for example, in a system double-earth fault—the temperature rise of one conductor only in a given cable would seem prone to set up severe mechanical internal forces, possibly leading to deformation of an unrestrained cable. Has any work been done to examine this condition and the behaviour of bends in the horizontal plane? Fig. 2 does not show how far apart are the practical working pressure and the pressure at which the elastic limit of the corrugated strip reinforcement is reached. Between these limits, is there a substantial margin for accommodation of static head and transient pressures owing to heating? The small number of barrier joints in actual use suggests that there has been little application so far in hilly country.

Mr. J. R. Harding (*at Southampton*): I suggest that the title of the paper is a misnomer, as it indicates a mass-impregnated cable in which a high pressure is employed to suppress ionization, whereas the cable is designed and manufactured as an oil-filled cable, and is dried and impregnated with a thin oil after sheathing, thus retaining the valuable feature of all oil-filled cables, i.e. automatic testing of the sheath under vacuum during manufacture. The only pressure required is a minimum of a few pounds per square inch above atmospheric. It has therefore little in common with the normal mass-impregnated pressure cable working at pressures of the order of 200 lb/in^2, for which the flat formation would be quite unsuitable.

I am not clear as to the necessity for the self-compensating strips on submarine cables except in shallow water, since the difference in the specific gravity of the oil and sea water would automatically ensure a positive pressure under all conditions of load.

Mr. A. H. McQueen also contributed to the discussion at Cardiff.

Messrs. J. S. Møllerhøj, A. M. Morgan, and **C. T. W. Sutton** (*in reply*): A number of points have been raised with regard to the design of the cable. The maximum a.c. design stress for 33 kV cable, which is given as 75 kV/cm, is not unduly low when one appreciates that the insulation thickness applied to 33 kV cables is determined mainly by considerations of mechanical strength. The minimum pressure of 7 lb/in^2 quoted in the paper applies to all dielectric thicknesses. Transient pressures occurring in the cable are very low as little longitudinal flow of oil occurs. Steel-wire reinforcement has not been used, generally for mechanical reasons and not because of abnormally high reinforcement and armour losses. In fact, some of the submarine cables that have been installed employ steel-wire armour. The self-compensating strips are desirable for submarine cables for laying in all depths of water, in order to control the method of self-compensation. Elimination of the corrugated strip for cables laid in deep water would not ensure regularity in deformation of the flat sides in varying load conditions.

Transposition of the cores is not generally used in modern installations as there is little variation in impedance between the centre and outer cores with the spacings between cores employed in the cables. The phenomena of indentation of the lead sheath by circumferential binding wires under very high fault-current conditions has not been observed, and it is not a limitation to the fault currents which could be carried by the cable.

Mr. Harding queries the name which is applied to the cable. We prefer to divide cable designs into two main types: those with fully impregnated dielectrics, and those in which a device such as gas pressure is introduced into the insulation to suppress ionization. The compression cable, which is generally placed in the same category as impregnated cable or gas pressure cable, does, in fact, use a fully impregnated dielectric, as in the oil-filled and flat pressure cables.

* MØLLERHØJ, J. S., MORGAN, A. M., and SUTTON, C. T. W.: Paper No. 1884 S, July, 1955 (see 103 A, p. 134).

DISCUSSION ON

'THE POTENTIALITIES OF RAILWAY ELECTRIFICATION AT THE STANDARD FREQUENCY'*

Before the SOUTHERN CENTRE *at* SOUTHAMPTON 17*th October, the* NORTH STAFFORDSHIRE SUB-CENTRE *at* HANLEY 26*th October, the* SOUTH MIDLAND CENTRE *at* BIRMINGHAM 5*th November, the* EAST MIDLAND CENTRE *at* DERBY 6*th November and the* WESTERN CENTRE *at* BRISTOL 10*th December*, 1956, *the* SHEFFIELD SUB-CENTRE *at* SHEFFIELD 20*th February, the* NORTHERN IRELAND CENTRE *at* BELFAST 12*th March, the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH 19*th March, the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL 1*st April and the* NORTH MIDLAND CENTRE *at* YORK 2*nd April*, 1957.

Mr. B. K. Pilkington (*at Southampton*): Is there any advantage to be gained from the use of low frequencies, or is this rather a case of heredity, and that having started with low frequencies they have been retained in later developments?

The authors have made an excellent case for standard frequencies, and they aim at increasing voltages to a limit which may become questionable in restricted places like tunnels, which indicates that lower voltages in such places are almost inevitable. I suggest that the many advantages to be gained by using standard frequencies might be usefully extended on financial grounds to the adoption of standard voltages such as 33 kV in the open, and say 11 kV in places where clearances are necessarily restricted.

Mr. K. Taylor (*at Hanley*): The major factors given in the paper in favour of the standard-frequency system are in connection with its lower first cost compared with a d.c. system, and particularly with respect to the overhead-line equipment. In Fig. 4 the comparison is made between a simple catenary equipment on the a.c. system and a compound catenary equipment on the d.c. system. While a simple catenary with a contact wire of $0 \cdot 166 \mathrm{in}^2$ cross-section may be satisfactory on a route where the traffic density is low and fairly slow moving, it may not be satisfactory where traffic is frequent and moving at high speed.

It is agreed that the a.c. equipment need not be as heavy as the d.c. equipment, but it may be necessary to use either a stitched or compound catenary equipment to suit traffic when operating speeds are in the region of 100 m.p.h.

Although the French use a simple catenary system on lines where the speeds do not exceed 100 km/h, for other lines they make adjustments to their equipment to make it suitable for speeds up to approximately 140 km/h. It seems possible that, for speeds in excess of this figure, they may be compelled to use a compound system. All such modifications increase the cost of the a.c. equipment and so reduce the difference between it and the d.c. equipment.

Further, on routes where the traffic density and train speeds are high, I suggest that a contact wire as small as $0 \cdot 166 \mathrm{in}^2$ may not have a sufficiently long life before it has to be renewed owing to wear. Perhaps the authors could state what type of pan strip and pressures they have in mind for use on this system.

Reference is made in the paper to the bonding and earthing of structures. It is suggested that bonding of the traction return rail can be dispensed with in some circumstances. Even though most of the return current may pass through the earth, some current will return through the running rails. We should not have to rely on the fishplate connections to carry this current as they are periodically removed for cleaning and lubrication. It is understood that, in some cases where bonding is not used, it has been found necessary to issue to the permanent-way staff a bond which they have to attach to the rails on each side of a rail joint before the fishplate is removed. I suggest that this is not really satisfactory practice, as men are apt to forget or wilfully ignore such safety appliances.

Where cables with metallic sheaths or metal pipes run parallel to the track they may carry induced currents as well as traction return currents. Have the authors any recommendations to make on the safety precautions which may be taken by staff before commencing work on such cables or pipes?

Mr. T. E. Calverley (*at Hanley*): When the use of rectifiers on locomotives and motor coaches came to the fore some years ago, I felt certain doubts concerning three aspects; namely the effect of harmonic currents in the traction motors, the interference with communication circuits owing to harmonic currents in the overhead system, and whether rectifiers of the mercury-arc type would operate satisfactorily under violent shaking conditions. My doubts were resolved after many experiments followed by satisfactory operation of rectifier-operated motor-coaches in traction service.

The power factors and harmonic currents given in Section 3.5 seem to be pessimistic. Recent investigations indicated that power factors of $0 \cdot 83$ at the locomotive are reasonable, which gives values of about $0 \cdot 8$ at the substation. The value achieved depends on many factors, one of which is the inductance in the d.c. motor circuit. With regard to harmonics in the overhead system, tests carried out on a motor-coach equipment while accelerating at just over full load current gave figures for the 3rd, 5th, etc., up to the 13th harmonic of 14, 6, 4, 2, 2 and 1%, respectively, while recent calculations on a large locomotive at rated load gave 17, 9, 5, $3 \cdot 5$, $2 \cdot 4$ and $1 \cdot 7$%, respectively. These figures, both for the motor-coach test and for the locomotive calculations are, in general, lower than the minimum figure quoted in the paper.

It is hard to credit the statement that rectifier locomotives should be no more costly than 3 kV d.c. locomotives, since the rectifier locomotive contains additional rectifiers, transformers and tap-changing equipment, which are only offset by the starting resistors.

Mr. D. H. Tompsett (*at Hanley*): It is clear from several Sections of the paper that calculation of rectifier-locomotive performance is important from the viewpoint both of the traction undertaking and the power-supply undertaking. In conventional rectifier analyses approximations are made in representing both the a.c. and d.c. circuits. These can lead to serious errors in the case of bi-phase equipments. The use of a modern high-speed digital computer permits a more rigorous treatment including finite d.c. inductance, discontinuous load current and complex a.c. system impedance. Mathematically what is required is a facility for dealing with sequential sets of simultaneous differential equations, the sets being defined by prescribed rules corresponding to the extinction or inception of anode currents. Applications of Deuce to such calculations have recently been

* WHEATCROFT, E. L. E., and BARTON, H. H. C.: Paper No. 1998 U, January, 1956 (see 103 A, p. 411).

described.* Extension of the computer programmes allows phase unbalances and the effects of resonant conditions to be calculated. It would appear desirable to make the fullest use of such facilities in assessing the relative technical merits of various alternative arrangements for the supply and traction equipments.

Mr. W. G. Robinson (*at Hanley*): The effects of dust and dirt on the operation of transformers and other parts of the electrical equipment have been mentioned in the discussion, but it should not be forgotten that the insulation of the overhead system is also exposed to dirt and general atmospheric pollution.

Conditions in this respect are worse in this country than on many foreign railways which form the basis of much of the data presented in the paper. The conditions under which the insulators have to operate may considerably influence the choice of clearance distances on the overhead system, and I should be glad to have the authors' comments on this point.

Mr. C. E. Maddock (*at Hanley*): With regard to the statement in Section 3.8 that induced voltages exceeding 1 kV were obtained in open communication lines running parallel to the 25 kV traction conductors, what would be the effect on twin overhead circuits of 6·6 kV running parallel to the conductors for one mile and separated by not more than 20 ft?

Mr. D. P. Sayers (*at Birmingham*): The paper impresses me with the fallibility of engineers and the dangers of standardization.

My earliest recollection of the subject goes back to an essay I had to write in my final examination on the relative advantages and disadvantages of alternating and direct current for railway electrification. At that time the old Brighton line was using alternating current, but soon afterwards the Southern Railway adopted 600 volts d.c. as the standard for all further suburban development. Two decades later, British Railways issued a report in favour of 3 kV d.c. for main-line electrification, but the ink is hardly dry when we are told that the railways are to be modernized using the 25 kV a.c. 50 c/s system.

It would seem clear that, with the 50 c/s a.c. system, the cost of substation and track equipment will be less, but the cost of the rolling stock will be greater because every locomotive must carry its own rectifier. Hence one would expect the relative economies to be influenced very much by traffic density, and I am surprised that the authors do not lay greater emphasis on this. According to Table 1, most of the experience of 50 c/s a.c. systems has been with the railways in France and Hungary, but are not conditions there quite different and traffic densities very much less than in Great Britain?

I gather that the detailed surveys now in progress indicate that the extent and cost of cabling the communication and signalling circuits may be appreciably greater than earlier estimates led us to expect. Have the authors any information on this point?

Mr. R. Mallet (*at Birmingham*): Would it be worth while electrifying an isolated section of line such as the Lickey incline near Birmingham? This is three miles long with an average gradient of one in 36, and it necessitates the continual employment of a large number of banking engines and their crews.

Heavy goods trains take as much as twenty minutes in going up the incline, and the smoke causes considerable damage to property.

As there is an adequate supply of electricity available in the immediate vicinity, the cost of providing a 25 kV supply would be low, and the economies in respect of manpower, reduced operating time and coal consumption would appear to be relatively high for the capital outlay.

* Denison, S. J. M., and Taylor, D. G.: 'The Use of Digital Computers in obtaining Solutions to Electric-Circuit Problems involving Switching Operations', *Proceedings I.E.E.*, Paper No. 2120 M, September, 1956 (103 B, Supplement No. 1, p. 35).
Calverley, T. E., and Taylor, D. G.: (see page 355).

Dr. W. G. Thompson (*at Birmingham*): To improve the transportation from the source of manufacture to the ports is an economic gain, and presumably the change-over to electrification will also assist the railways in their competition with other forms of transport.

In the North and Midlands a large proportion of the railway traffic is industrial and goods, whereas in the Southern Region extensions of electrified lines are in the nature of suburban electrification handling a large proportion of passenger traffic.

It is difficult to compare different railways, particularly oversea examples, on the same basis, and this should be borne in mind when advocating a particular form of power supply or locomotive design. Economic transportation is the overriding requirement; for example, with multiple stock it is necessary economically to put electrical equipment below deck level, and thus in design and layout the electrical engineer does not have a free hand.

In the 50 c/s electrification of the Hollentahl line experiments were made with various types of rectifiers and a.c. commutator motors, and the tests emphasized the need for simplicity in the design of equipment.

In comparing 50 c/s a.c. with d.c. electrification, more rectifying equipment has to be distributed amongst a.c. trains than is required for d.c. substations. Whether this will be economic depends on the traffic density. Oversea, often the only access to the substation is along the track itself, and there is thus some advantage in having converting equipment on the train, which can be taken to the depot for maintenance without interrupting the service.

It should be noted that the weight of a 50 c/s motor is greater than that of a $16\frac{2}{3}$ c/s one. This is interesting to the student as an electrical paradox, but is an important consideration from the point of view of bogie design.

Railways working with rectifiers provide an insight into the question of harmonics, but they should be considered in proper perspective. The general public using the railways do not worry about electrical engineers' problems, provided that they are not inconvenienced by them. To obtain the most economical solution, equipment should be selected on its practical merits rather than from ideal considerations.

Mr. H. K. P. Burt (*at Birmingham*): One of the restrictions in our present transport system is caused by the inability of railways to carry bulky or tall loads. The problem will be aggravated by reducing headroom in tunnels and under bridges, while innumerable road level crossings must be borne in mind. It is time that we looked well to the future and ensured that the railways are altered to suit modern traffic requirements, and in this connection I should like to know whether the present system can be modified to eliminate overhead systems, e.g. by using a much higher frequency with induction pick-ups or by siting the live rail at the side or even underground.

Dr. E. Friedlander (*at Birmingham*): Dr. Thompson refers to an apparent paradox that a 50 c/s motor is heavier than a $16\frac{2}{3}$ c/s one. The paradox disappears if the frequency is referred, not to the supply, but to that frequency which is responsible for the power conversion. This frequency, for instance, is the armature frequency in the d.c. motor. A d.c. motor may thus, in reality, be lighter than an a.c. machine.

Mr. Burt suggests the advantages of a third-rail supply for long-distance electrification of lines having a high traffic density. Would the authors agree that this is undesirable in view of the possibility of accidents to small children? These are known to have occurred at a regrettable rate in suburban areas, and would probably be much more frequent still on railway lines passing through rural districts.

Mr. G. Smith (*at Derby*): With regard to Section 3.1 there are

two most important features which must be achieved before any new form of rolling stock may be considered to be successful. First, it must be reliable; and secondly, it must require the minimum of maintenance and be capable of being maintained by relatively inexperienced personnel.

With regard to the first point, all three types of rolling stock for standard-frequency operation referred to by the authors, i.e. the a.c.-motored type, motor-generator type with d.c. or a.c. motors and the rectifier type with d.c. motors, possess the necessary degree of reliability. There is probably more proof of this on the first type mentioned than on the other two, but experience on the French Railways over the past few years appears to suggest that both the motor-generator and the rectifier types are about equally reliable. One must also consider the auxiliary equipment, and it is important that this be reduced to the minimum since it can so often be the cause of breakdowns.

The authors have touched on the second point only briefly, but it would appear from a study of the installed apparatus that the rectifier type with apparatus on the locomotive comprising transformer and rectifier, particularly if of the semi-conductor form, may require the least maintenance. This is of importance in oversea application, where highly trained maintenance staff may not always be available.

A problem which emerges from the application of rectified direct current to traction motors is that of commutation, but this has only been very briefly referred to in the paper. It requires special study, and perhaps the authors could state whether 20–30% smoothing of the undulations has been found to be acceptable on equipments not American in origin.

Little mention has been made of energy consumption in the paper, although it must have been taken into account in the preparation of Table 4. The rectifier locomotive, without regeneration, is unfavourable when compared with a motor-generator locomotive, and the authors' comments on the importance of this feature would be appreciated with particular reference to main lines having a high traffic density.

Mr. L. F. Garner (*at Derby*): In view of the fact that, for long distances, Post Office and other cables would be placed underground in close proximity to the track, have any tests been made to assess the magnitude of stray direct currents? In consequence, has it been thought necessary to apply cathodic protection or some alternative to protect the metallic sheaths of these cables?

It is also known that the normal type of induction watt-hour meter is considerably influenced by harmonics of the order indicated in the paper. Have any tests been made to determine the inaccuracy in precision-type metering which would be used by the C.E.A. or Area Boards for the bulk supply points?

Dr. D. R. Hardy (*at Derby*): The authors, in their appreciation of rectifier rolling stock, refer to the 'well-proven d.c. traction motor'. Whilst this may be the case with motors supplied with a voltage having negligible power-frequency harmonic content, it would be appreciated if the authors could provide more detailed evidence of satisfactory operation when the motor voltage contains harmonics with amplitudes of up to 30% of the fundamental. In Section 3.5 the authors refer to 20–30% smoothing of the undulations. Does this mean, as the terminology certainly suggests, a reduction of 20–30% of the voltage harmonic content or should it be a reduction to 20–30%, expressed as a percentage of the fundamental amplitude? The size and weight of the smoothing choke will obviously depend on this quantity, and will increase as the permissible harmonic voltage content is decreased.

The rectifier system known as a 'multiple-voltage anode connection' is said to reduce the choke dimensions. In this system, a simple diode is connected in series with the neutral or centre point of a bi-phase transformer secondary winding, and other grid-controlled rectifier units are connected at suitable points along the two arms of this winding. Although the system may be used for starting and speed-control purposes, it does not meet the requirements of the current British Railways specification. Even so, it may have other advantages which make it worthy of further consideration, and any information which the authors may have on this type of system will be most welcome.

Finally, I would like an explanation of Fig. 3 as I am unable to understand, or correlate, with any other data given in the paper, the scale of the ordinate axis of the symmetrical-component diagram of this Figure.

Mr. E. M. Morgan (*at Derby*): I believe that the first design for a rectifier-type locomotive was evolved in Germany over 30 years ago. Can the authors give any particulars of this design, and can they state whether a rectifier locomotive was, in fact, built at that time?

With regard to dual-system operation (Section 3.2), details were given at the Annecy conference, organized by the S.N.C.F. in 1951, of a motor-generator locomotive having a convertor set comprising a single-phase 50 c/s induction motor driving three d.c. generators. For operation on the 1·5 kV d.c. system the generators were used to 'buck' or 'boost' the supply voltage and thereby control the voltage applied to the traction motors. Another a.c./d.c. locomotive built in France was equipped with a d.c. motor/single-phase alternator set for use when operating on direct current. The alternator of this set supplied the main transformer secondary winding functioning as an auto-transformer and feeding the 50 c/s a.c. traction motors in the same manner as when operating on an a.c. supply. It would be interesting to know whether any information is available concerning the operating performance of either of these types of locomotive.

Dr. J. E. Brown (*at Bristol*): From the point of view of the student of dynamo-electric plant, one of the most interesting features of the paper is the brief survey of the alternative types of rolling stock, given in Section 3.

It seems reasonably well established that, when the driving motors are of the series commutator type, the operating frequency should be much less than 50 c/s, because of effects resulting from the 'transformer e.m.f.' in the coils undergoing commutation. It would appear to be a logical conclusion, from the maintenance point of view at least, to make the operating frequency zero, i.e. to use direct current. However, in my opinion, it would be evidence of undue complacency to accept 'the well-proven d.c. traction motor' without intensive investigation of the alternatives; the use of squirrel-cage induction motors, for example, should offer considerable saving in maintenance costs alone. For this reason, it would be interesting to have more information on the latest experimental phase-convertor and frequency-changer installation in use on the French Railways; the precise form which this takes is not at all obvious from Section 3.1.2 of the paper.

It appears that the advantages of this experimental system tend to be outweighed by the disadvantages of complication and lower power/weight ratio. These disadvantages might, however, be overcome if it were possible to incorporate the phase-conversion and frequency-changing processes in a single self-propelled machine. A colleague and I are investigating several topics which have a bearing on this general problem, but the results are not yet sufficiently complete for publication.

Would the authors agree that this type of standard-frequency electrification would be less troublesome from the aspect of telecommunication interference than that employing rectifier rolling stock? It would be interesting to know whether there has been any information on this matter from the experiments made on the French Railways.

Mr. E. N. Evans (*at Bristol*): I question the statement in the paper that standard-frequency a.c. drive really is the cheapest method, particularly when considered in terms of basic fuel used.

Have the authors any figures available to show the cost per horse-power-hour at the traction motors or the cost per ton-mile of the following alternatives, assuming that train heating absorbs 15% of the total power required?

(i) A 50 c/s a.c. system, the cost of which is based on a standard Area Board tariff plus the capital depreciation and maintenance charges for track equipment, train-heating equipment and the running costs of the train heating using solid fuel or electricity.

(ii) A heavy-oil-engine system using direct-drive traction and utilizing waste heat for the train heating. Possibly the overall efficiency of such equipment is of the order of 70%.

(iii) Heavy-oil engine, driving a generator with final electric drive, and again using waste-heat recovery for train heating.

On the basis of overall efficiency it would appear that, from basic fuel to traction wheels, the figure might be about 12–15% on the Grid system and about 65–70% on an oil-engine electric system with waste-heat recovery.

In order to decrease the weight of the mobile equipment and possibly increase the pay load, is there not a possible case for adapting aircraft practice of using 400 c/s machines, with consequent saving in both weight and size?

In Table 4 can the authors explain why the interest and depreciation figures are so extraordinarily high? Is it because of an extremely low load factor?

Dr. E. G. Ashton (*at Sheffield*): As a student I was connected with proposals to electrify railways at a frequency in the neighbourhood of 50 kc/s. The idea was to avoid the contact wire and to pick up all the energy requirements by induction. Of course, mercury rectifiers were to be used, with d.c. motors driving the axles.

The proposals originated in France, and I understand that the scheme has actually been carried out in Russia on a small scale. When using the 50 c/s system, however, the complication of conversion to direct current should not be necessary, at least on motor-coach trains.

In Section 3.1.1 the authors have given a very fair summary of the problem of the 50 c/s motor. In comparing the weights per horse-power for $16\frac{2}{3}$ and 50 c/s systems, it should be remembered that the higher-frequency motors have not been in construction very long, and that some reduction in weight should be expected as experience grows.

The improvement over the years in $16\frac{2}{3}$ c/s motors was almost spectacular. For example, when the Gotthard freight locomotives were rebuilt, the 590 h.p. motors of 1919 were replaced by 960 h.p. motors in 1943. The same stator frames were used, but the axial length of the windings is now only five-eighths of what it had been, in spite of the 61% increase of output.

Lastly, the authors do not mention that the 50 c/s motor has characteristics superior to those of the d.c. motor. This is because the reactance of the windings results in a steeper slope of the speed/torque curve and so the power does not decrease so rapidly when the speed rises.

Mr. H. Newsam (*at Sheffield*): The authors have made it clear that the paper is based very largely on investigations of the electrification of main lines of low traffic density, but they conclude that the a.c. system at standard frequency is likely to be the most economic for all future main-line electrification work. I feel that this is rather a sweeping statement.

I should like to know what has been included under 'operation' in Table 4. The figures for 'interest' give an indication of the capital cost involved, but it would be interesting if the authors could indicate the distribution of capital cost between the power-supply system and the rolling stock. The case for a.c. electrification rests largely on the savings that can be made in the substations and overhead distribution system. In general, the rolling stock is likely to cost more than for the d.c. system.

Since the paper appeared the British Transport Commission has published a document entitled 'The System of Electrification for British Railways', in which it is stated that the capital cost, including rolling stock, of electrifying the Euston–Manchester–Liverpool lines on the 25 kV a.c. system is estimated to be approximately 4·7% lower than the capital cost using the 1·5 kV d.c. system. It is also estimated that the annual costs for maintenance and depreciation (fixed equipment, signalling and motive power), current and interest would be approximately 8% lower for the a.c. than for the d.c. system. These estimates apply to lines of high traffic density, and the estimated savings are considerably less than those given by the authors in Table 4.

For locomotives and motor-coaches having the same number of motored axles, I should expect an a.c. locomotive to cost approximately 10–15% more than a corresponding d.c. locomotive, and the electrical equipment for a motor-coach to cost approximately 20–25% more. However, owing to the higher adhesion to which a.c. locomotives can be worked with the motors in parallel and fed from relatively constant-voltage tappings on the transformer, it is possible in some cases to use four-axle a.c. locomotives where six-axle d.c. locomotives would be required. In such cases, there is likely to be little difference in the capital cost of motive power, but it is not by any means universally the case that advantage can be taken of this feature.

It appears that the d.c. motor fed through static rectifiers on the vehicle is becoming generally accepted as the most suitable at present for both locomotives and motor-coaches. I cannot agree with the authors that the greater maintenance and higher unsprung weight are the main objections to the a.c. commutator motor. I feel that the repercussions of its greater diameter on the design of the mechanical parts and the effect of its heavy current on the control gear are the major factors, although I agree that the maintenance of the a.c. motor is likely to be greater than that of the d.c. motor.

Mr. W. Szwander (*at Belfast*): The 'battle of the systems', referred to by the authors, appears to be drawing to a conclusion with a complete victory for the standard-frequency a.c. system. This is strongly proved by the recent developments in France and Great Britain. It would be hard to believe that from now onwards any new railway electrification scheme (as distinct from continuing electrification started in the past) would be based on any other system. While admittedly any purely urban railway would be an exception to the above statement, this would hardly be the case with suburban lines, which practically always are sufficiently closely integrated to outgoing main lines to justify using on them the same standard-frequency system, which incidentally has particularly suitable starting features. In France the enthusiasm in favour of the standard-frequency system is growing, which is significant because it is based not only on theoretical studies but also on several years of practical experience with that system. According to information published in August, 1956, by Garreau, in the case of the standard-frequency, as compared with the 3 kV d.c. system, the cost of fixed installations is 23% lower, the cost of driving vehicles 12% lower and the operating costs (power, maintenance, etc.) 7% lower. The lower cost of locomotives and motor-coaches is particularly significant and points to the great gains possible owing to the extremely favourable adhesion properties of the driving vehicles with all-parallel connection of the motors, as they can be used in the standard-frequency system. The decision of the British Transport Commission and also the latest trend in France, which incidentally follows a period of experimenting with various alternatives, favour d.c. motors supplied from rectifiers mounted on the driving vehicle. This appears to be

the most promising solution, particularly in conjunction with the development, already in progress, of the semi-conductor (germanium, silicon) rectifiers. Great advances in this direction can be expected during the coming years. One thing to be regretted in this connection is the impracticability (in the case of mercury-arc rectifiers) or the impossibility (when using semi-conductor rectifiers) of the application of regenerative braking, which, on systems with high traffic density like that in Great Britain, would otherwise be very desirable. It is assumed, of course, that the usual rheostatic braking may be the standard feature of the rectifier locomotives and motor-coaches, the saving on maintenance of the air brakes justifying the extra cost and complication of the control equipment.

Mr. C. Snowdon (*at Belfast*): Whilst there may be many justifiable arguments for the various forms of railway electrification outlined in the paper, it is felt that Section 3.9 should not go unchallenged.

It is very surprising to find arguments based on the archaic system of railway signalling still in vogue. Arguments such as the need for more semaphore signals with d.c. than a.c. systems because the heavier d.c. structures and line work are more liable to obstruct the driver's vision, together with the developments of special d.c. track relays and the use of audio or 'musical' frequency signalling, appear to indicate that this antiquated state of affairs is to be perpetuated. It is a sobering thought to realize that there is not, in the majority of cases, any means of communication between the driver and the guard of a train, or with the rest of the world, other than writing messages on pieces of paper, tying them to potatoes and flinging them out of the window when passing some station en route. (This refers to a serious train accident which occurred a few years back.)

I would seriously suggest consultations between the railway authorities and aircraft communication engineers, whose job is much more difficult and who have been quite successful in their efforts.

Mr. J. L. Egginton (*at Edinburgh*): The object of electrifying at the standard frequency is to make use of public supplies of electricity, and the views of an engineer engaged in public supply may therefore be of interest.

The reasons for choosing a voltage of 25 kV are noted. In any event, transformers would be required, and the voltage on the output side is therefore immaterial, but as the railway supply will operate with one phase earthed, this corresponds to a standard 44 kV 3-phase system. 44 kV is not standard in this country and necessitates the use of special switchgear and cables unless the next higher standard of 66 kV is to be adopted. A railway voltage of 20 kV would have enabled standard 33 kV gear to be used.

As shown in the paper, railway loads are 'peaky' in nature, and to avoid undue fluctuations of voltage which might affect the other consumers, it is necessary for them to be connected to the system at a point where the short-circuit level is high. There are few cases where it would be possible to connect a railway load to any point on the system other than the 132 kV Grid. The nature of the load also makes it necessary to rate equipment on the r.m.s. current and not the 30 min maximum-demand current.

By connecting to the higher-voltage system, the difficulties due to negative-phase-sequence currents are less onerous. With modern generators it is necessary to limit the unbalance to 10% of the machine rating. The negative phase sequence will be distributed between machines on the basis of the negative-phase-sequence reactance in the machines and in the system. With the proportion of railway loads contemplated in south Scotland, no trouble is expected, except in conditions where a relatively small generator may be running at a point near a heavy railway load. In such cases the machine might take more than its fair share of negative-phase-sequence current, and it would be necessary either to run additional generating plant in the steam station or to shut down the small generator to avoid damage. The possibility of having devices to give indication or alarm when negative-phase-sequence current on generators is excessive is under consideration.

It is not anticipated that trouble due to harmonics will occur following the decision to connect railway supplies at 132 kV, but this is based on the assumption that the values of harmonics will be considerably lower than those given in Section 3.5 of the paper.

A power factor of 0·7–0·8 is low; the supply engineer would prefer to see some measure of reactive compensation on the railway system. The obvious place is on the locomotives, where the benefit of higher power factor would be felt on the railway overhead system. There may, however, be difficulties owing to the question of weight and space on the locomotive. In any event, power-factor correction at a point where the value of harmonics is high might lead to difficulties, and this should be seriously considered by the authors.

In the last paragraph of Section 3.6 it is suggested that the a.c. traction supply might be tapped for limited electricity supplies to under-developed districts. However, in view of the voltage variations of the order of 20% or even 50% suggested elsewhere in the paper, it is unlikely that satisfactory supplies could be given.

A point of concern to the supply engineer is the return current from the trains to the substations. There is always a possibility that this will find its way into the supply-system cable sheaths, etc. Electrolysis is not a hazard with alternating current but the possibility of overheating, particularly under fault conditions, has to be borne in mind.

Mr. P. R. Dunn (*at Liverpool*): Many considerations arise in the choice of a system for new work, but of the items enumerated by the authors, three seem of special significance. These are as follows:

(i) The Continental developments and experience with 50 c/s commutator traction motors.

(ii) The advances in rectifier rolling stock equipped with d.c. motors with advantages which this combination provides of improved adhesion from parallel operation and with the further prospects opened up by the recent developments in semi-conductor rectifiers.

(iii) For this country, in particular, the ready availability at many points of direct supplies from the 132 kV Grid system, capable of absorbing without special provisions the unbalanced loadings arising from single-phase a.c. operation and the harmonics to be expected from rectifier locomotives.

If one has any criticism of the paper, it is that the authors have given, by quoting the case illustrated in Fig. 4, an unrepresentative impression of the economies in line equipment arising from the use of high-voltage alternating instead of direct current. I would be interested to know whether they have considered, for oversea use, the substantial economies in the d.c. case which would result from the use of a steel catenary paralleled by aluminium feeders carried on the structures. For more general application the lightweight line equipment possible with the high-voltage a.c. system will more often require automatic tensioning if high-speed running is contemplated. If this is coupled with the magnitude of the extra civil-engineering work required in highly-developed countries to give the requisite line-work clearances for h.v. a.c. systems, we may find the comparison based on line equipment only is much less favourable to the a.c. system. There are, no doubt, substantial overall economies to be expected from the use of the h.v. a.c. system, but, in general, these may reside to a smaller degree in the line equipment than would be inferred from Fig. 4.

The paper was written in 1955. The subsequent adoption by British Railways of 25 kV a.c. for their main electrification programme and the speed with which the electrification is to be carried out should give an early opportunity for substantiation of many of the points advanced in the paper.

Col. G. W. Parkin (*at Liverpool*): Assuming the paper to be an academic exercise one might start off with an appreciation or a survey of the problem leading up to a plan of action, and would set down in such sequence 'aim', 'factors', 'courses open', and finally 'the plan'.

The 'aim' in this exercise, it will probably be agreed, is clear, but the 'factors' will vary with each situation, multiplying the 'courses open' and rendering more difficult the summing up leading to the recommended 'plan'. Accordingly, I venture to suggest that one exercise, i.e. that given in Table 4, which is for a single-track project of low traffic density, or indeed one exercise only which might be taken over any specific route cannot necessarily establish the case for one general system of electrification.

Thus the estimated lower annual costs of the 50 c/s a.c. scheme as compared with the 3 kV d.c. alternative presumably will include no major expenditure due to extensive modifications to existing signalling installations depending on 50 c/s a.c. track circuits nor any appreciable expenditure on bridge lifting.

We must admit that the potentialities of electric traction at standard frequency are tangible and fascinating, and whereas the main line selected by the B.T.C. for the comparative survey justifies such choice of system (for main-line working), one hesitates to add as a corollary that a case is thus also made for the working of high-traffic-density urban and suburban services as, for example, the existing d.c. electrified lines in this area.

With train headways of only two or three minutes, economy in train weight is vital if operating costs are to be kept at an economic level, and inevitably a.c. trains carrying transformers and rectifiers must be substantially the heavier. The following comparisons of fixed and mobile equipment capacities with respect to the local electrified lines will emphasize the points.

Line	No. of motor-coaches	Aggregate installed traction motor capacity	No. of substations	Aggregate installed capacity of substation plant
		MW		MW
Liverpool–Southport	60	42	10	17·54
Mersey–Wirral	43	17·6	9	8·1

It would thus appear that the conversion of such lines to standard-frequency traction would call for the mobile rectifying plant to be more than doubled in capacity and housed in cramped accommodation, making examination tedious. I would like to have the authors' views on this subject.

Finally, most tunnels, and not only the Severn and Mersey, are wet. What degree of immunity from insulator breakdowns is anticipated in such locations?

Mr. R. S. Wignall (*at Liverpool*): The authors are in no position to be dogmatic about power factor, and hence they have given their data in a conservative manner. The higher figures of power factor are, no doubt, related to the French references given in the paper, but unfortunately they represent an optimism which is enhanced by the presence of unity-power-factor convertor machines on the same system. Wholly rectifier systems such as our own will have no such advantage, and their power factor will, of necessity, need some expensive correction equipment at the substation if the supply undertaking's requirement of a minimum power factor of 0·9 (lagging) is to be realized.

A.C. traction would not be a suitable proposition in certain projects unless some form of dynamic braking could be incorporated. With rectifier-fed motors, no simply applied solution for traction applications has been reached in the field of regeneration, but I am surprised that the authors have not mentioned the potentialities of rheostatic braking. The problem is analogous to that of the Diesel-electric locomotive—an increase of about 4 tons in weight for a 2000 h.p. locomotive being a typical requirement for rheostatic braking. It is not suggested that such provision should be made for this country as it is not justified, but it is worthy of mention in connection with certain oversea projects, such as those used in illustrating the paper.

Mr. T. Makin (*at Liverpool*): The ratios of interest and depreciation for each of the four systems shown in Table 4 are approximately the same, i.e. 5 : 1. Would the authors consider giving details of the actual percentage rates?

Mr. S. D. van Dorp (*at York*): In Section 3.3 the authors refer to one of the most serious drawbacks of railway electrification at the standard frequency as compared with the lower frequencies in common use on the Continent. Owing to the increased reactance, which is directly proportional to frequency, it is necessary to increase the voltage in order to maintain the same substation spacing. It has been shown that 25 kV at 50 c/s is approximately the equivalent of 15 kV at $16\frac{2}{3}$ c/s from this point of view. Since large distances between substations is one of the main arguments in favour of a.c. electrification, it can be said that an increase in voltage is inherent in an increase in frequency. This brings with it the difficulties arising out of the increased electrical clearance to earth in tunnels, etc.

In the paper no mention has been made of the three-conductor single-phase system utilizing one contact wire, one feeder wire and the running rails. This system has been used fairly extensively in the United States on 25 c/s systems, e.g. on the New York, New Haven and Hartford Railroad.

In such a system the contact wire could be energized at 6 kV relative to the rails and the feeder wire at 19 kV but of opposite polarity. At intervals of a few miles auto-transformers are connected across the 25 kV supply of the contact wire and the feeder wire and the tapping is taken out a quarter of the way along the winding from the contact-wire end and connected to the rails.

The power supplying the train is then carried for the greater part of the distance at 25 kV and only for a small distance at 6 kV, i.e. for the distance between auto-transformers on either side of the train. Thus the spacing of the power-supply points corresponds to that used with 25 kV, although the contact wire is only energized at 6 kV. Hence only small clearances are necessary. This would greatly reduce the constructional problem of taking the contact wire through tunnels, under low bridges, etc. No problems would arise with the feeder wire, as it could be transferred to cables or taken over the top as open wire. The addition of one wire should be a relatively simple matter. It could perhaps be suspended on the outside of the structures supporting the catenary.

I understand that British Railways are proposing to use a dual-voltage system, having 25 kV on the contact wire in the main, and 6 kV through low-clearance tunnels, etc. This brings with it the complication of additional equipment on all locomotives and motor-coaches and on the track wherever a change in voltage occurs.

It seems that the three-wire system is a potential method of railway electrification at the standard frequency deserving very careful consideration, and is a practical and satisfactory alternative to the dual-voltage scheme. I should like to have the authors' opinion on the system.

Long distances between substations are a considerable advantage in non-industrial countries or where large agricultural areas exist between industrial centres. But in this highly industrial

country, with its very extensive power-supply network, the locating of substations cannot be advanced as a problem.

If serious objections exist to my first suggestion of a three-conductor system, would it not be preferable to operate at a compromise voltage of, say, 15 kV? There would be virtually no increase in the cost of overhead equipment, since at 25 kV the wire size is determined to a large extent by mechanical strength, rather than electrical considerations, and the size and cost of insulators would be correspondingly reduced. More substations would be required and a certain amount of civil engineering would no doubt be necessary, but obviously less than if only 25 kV were adopted.

Messrs. E. L. E. Wheatcroft and **H. H. C. Barton** (*in reply*): The choice of the electrification system must suit the character of the railway. For a 'subway' or suburban railway which is limited to built-up areas, clearance difficulties will obviously favour a low-voltage d.c. system. Mr. Parker refers to suburban sections of main-line railways, where frequent overbridges, high traffic density and the ready availability of power at medium voltages often give the same answer. In such cases it is necessary to consider how far the electrification is likely to be extended. If these routes also carry through traffic, beyond the suburban area, the 50 c/s system may be justified. The use of low frequencies referred to by Mr. Pilkington was originally adopted in order to obtain a more satisfactory a.c. commutator motor; with rectifier equipments low frequencies are a disadvantage because the transformer size is increased. We thoroughly endorse Dr. Thompson's remarks that the system which is selected should have practical merits and give the best service to the users of railways.

Dr. Brown mentioned the use of squirrel-cage induction motors and Mr. Smith referred to regenerative braking as advantages which may be obtained with the motor-generator type of locomotive. These advantages are not generally sufficient to overcome the disadvantages which rotary machines have over rectifiers; indeed, the almost complete change-over to rectifiers in d.c. substations may be cited as a comparison. For some special applications, however, such as banking referred to by Mr. Mallet, the inherent regenerative feature and high power factor may make the motor-generator locomotive worth while, although regenerated power can be an embarrassment when the basic load is not large enough to absorb it. For this reason rheostatic braking may be preferred, and, as mentioned by Mr. Szwander, this feature can be obtained easily with rectifier locomotives. It is interesting to note, however, that the German brown-coal industry has some rectifier locomotives equipped with regenerative brakes. We agree with Mr. Newsam that the large diameter of the a.c. commutator motor will complicate the locomotive mechanical parts. We thank Dr. Friedlander for solving the electrical paradox of the increase in weight of an a.c. commutator motor with frequency. The factor of 20–30% smoothing of undulations referred to by Dr. Hardy is the ratio of half the ripple amplitude to the mean direct current. This amount of smoothing has given satisfactory operation with rectifier locomotives in France and America.

The comparison in line construction costs given in Fig. 4 refers to oversea projects where speeds were relatively low. We agree with Mr. Taylor that high-speed operation will increase the cost of a.c. line construction more than is the case with heavier d.c. equipment. High corrosion rates occurring in the localities of these oversea projects precluded the use of steel catenary referred to by Mr. Dunn; we agree, however, that aluminium feeders may be justified for d.c. equipments where corrosion rates are low. We have considered the three-wire distribution system mentioned by Mr. van Dorp, but a straightforward supply at high voltage was cheaper in the cases we examined because of the comparative freedom from infringing structures. We agree that, where possible feed points are numerous and infringements frequent, a compromise voltage may be the most suitable technical and economic choice. We consider that pollution of insulators referred to by Mr. Robinson presents a more serious problem than wet situations mentioned by Mr. Parker; the latter problem can be eased by the use of 'anti-fog' type insulators. More frequent cleaning appears to be the only solution in areas where pollution is high. Although the suggestion of Mr. Burt and Dr. Ashton is most attractive, it does not seem probable that there will be an early solution to the problem of transmitting power to a moving train without the use of contact wires or rails. Messrs. Taylor and Egginton raise the question of earth currents; in general, these present less difficulty with a.c. systems than with d.c. ones owing to the lower currents and the negligible electrolysis effect. Adequate earthing of local equipment must, however, be provided in order to prevent the build-up of voltages dangerous to maintenance personnel. For cable sheaths this may take the form of neon discharge tubes. In the 6·6 kV case cited by Mr. Maddock the induced voltages would be liable to exceed safe working limits.

The cost of immunizing communication and signalling circuits in this country, as mentioned by Mr. Sayers, is outside the scope of the paper, but investigations which we have made since the paper was published reveal that the figures quoted for oversea projects tend to be high. We agree with Dr. Brown that the motor-generator locomotive produces less interference, but not sufficiently less to eliminate the need for cabling.

The item 'operation' in Table 4 queried by Mr. Newsam is the cost of locomotive crews and of staff at the main control centres for supervising the operation of substations. The ratio of capital cost between the power supply system and the rolling stock is as follows:

	1·5 kV d.c.	3 kV d.c.	$16\frac{2}{3}$ c/s a.c.	50 c/s a.c.
Transmission, substations and track equipment	139	100	69	66
Rolling stock	28	31	35	34
	167	131	104	100

We have no data to enable us to assess the effect of the cost of train heating in the three alternatives Mr. Evans mentions; indeed on many oversea projects train heating is not required. Any theoretical advantages obtained by using a prime mover with waste-heat recovery might be outweighed by maintenance costs. In Table 4 interest is at $4\frac{1}{2}$% and depreciation is based on the sinking-fund method with asset lives varying from 25 to 40 years. For lines with a low traffic density, interest and depreciation amount to a high proportion of the annual charges.

We agree with Mr. Calverley that the figures given for power factor and harmonic currents in Section 3.5 have been proved to be pessimistic by tests carried out at Heysham, the results of which have been published since the paper was written. The reason for this discrepancy has now been revealed by recent researches carried out by Mr. Calverley and others in which, as Mr. Tompsett says, the high-speed digital computer enabled a rigorous treatment of the problem to be made. We thank Mr. Egginton for giving the views of a public supply engineer, and we are interested to hear that no trouble is expected with the proportion of railway loads contemplated in south Scotland. We agree that special consideration must be given when railway supplies are required at locations which are near small generating stations. The symmetrical component diagram given in Fig. 3, which is referred to by Dr. Hardy, shows the relative values of the positive- and negative-sequence components. The ordinate of the positive sequence, if multiplied by $\sqrt{3}$, gives the total power in kilowatts.

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EARTH-ELECTRODE SYSTEMS FOR LARGE ELECTRIC STATIONS

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SUMMARY

Interconnected systems have increased considerably in recent years, and the large possible earth-fault currents resulting require further thought being given to earth system design, especially in areas of high soil resistivity. The paper discusses the special practical problems of the design, construction and testing of earth electrode systems for stations with possible earth-fault currents in excess of 3 kA. The basic components are reviewed, and principles of design are suggested for power station and large substation earthing installations. Several examples are considered in detail and brief notes are given of a number of other stations. The measurement of the dissipation resistance of large earth electrodes is discussed, and new techniques of resistance measurement which have been specially developed for use with large installations are described.

(1) INTRODUCTION

The increasing concentration of generating plant and, in Britain, the direct earthing of transformer neutrals on the 132 kV and 275 kV transmission systems have resulted in a great increase in the possible magnitude of earth-fault currents with consequent imposition of higher stresses on earth-electrode systems.

In areas of low soil resistivity little difficulty has been experienced in obtaining satisfactory earth-electrode systems, and the problems arising when traditional design methods are employed in areas of very-high-resistivity soil have been largely ignored. In South Wales a number of stations have been built on limestone, sand or peat, and the difficulties caused by the high resistivities encountered have necessitated a complete reconsideration of the approach to earth-electrode system design. The information contained in the paper has been based on experience generally obtained at sites with high soil resistivity, but it will be equally applicable in areas of lower resistivity when the new factors previously mentioned are taken into consideration.

The paper deals with some of the practical problems encountered in the design, construction and testing of earth-electrode systems for generating stations and large substations, where the possible maximum earth fault currents are in excess of 3 kA, although many of the comments are applicable to smaller stations.

(2) REQUIREMENTS OF AN EARTH-ELECTRODE SYSTEM

A satisfactory earth-electrode system must be capable of dissipating into the earth the maximum current which may flow through it without causing damage to life or plant by reason of high potentials, potential gradients, thermal or mechanical stresses.

Earth-electrode systems should be designed in the first instance to conform with the above requirements when carrying normal power-frequency currents. They will also frequently have to carry high-frequency currents due to lightning, and a proposed design should ensure that the impedance presented to high-frequency currents does not differ greatly from the power-frequency impedance. This is not difficult to achieve in the case of electrode systems of small area, such as are found in distribution substations, where the impedance to steep-fronted waves can be virtually the same as the d.c. resistance. In the case of the large stations considered here, however, the inductance of the various interconnections is frequently considerable. It is therefore essential to ensure that an appreciable proportion of the total dissipation conductance of an earth-electrode system is concentrated at the points most likely to be affected by surges.

The problems associated with the potential rise of an electrode system with respect to earth under fault conditions and the associated potential gradient are mainly concerned with the danger to life, although in the case of telephone equipment damage to plant is also a possibility. Much work has been carried out on the aspect of danger to life due to electric shock, but in practice the conditions are so variable that, in the absence of adequate theoretical knowledge, it is necessary to work to empirical rules which appear to give reasonable service.

The V.D.E. specifies maximum contact voltages and potential gradients, related to the time for which the voltage is applied (see Fig. 1), whilst the British Post Office specifies that the

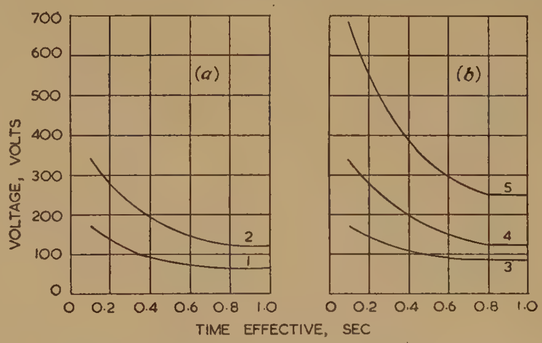

Fig. 1.—Permissible earth potentials as given in V.D.E. Draft Specification 0141/54

(*a*) Contact voltages: 1—Outside the installations.
2—Inside the installations.
(*b*) Step voltages: 3—Outside installations on busy thoroughfares.
4—Inside and outside excluding 3.
5—In outdoor switching stations when wearing insulating shoes.

maximum potential of an earth-electrode system in a station must not exceed 430 volts if an unprotected telephone line is to enter that station. If the voltage is likely to exceed this value, special protection must be provided for the telephone equipment. Until more specific rulings are given, the Post Office maximum of 430 volts has been used as a criterion of design efficiency.

It will usually be found with large installations that if a satisfactorily low dissipation resistance is obtained steep potential gradients will not occur. Where small substations have large prospective earth-fault currents, localized points displaying high surface-potential gradients can generally be avoided by a careful choice of electrode depth and the insulating of surface connections.

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(3) BASIC ELEMENTS OF AN EARTH-ELECTRODE SYSTEM

The most fundamental aspect of electrode design for large stations is that the earth system must be considered as a complete entity. The practice of providing one or two isolated earth electrodes connected to the main earth busbar via test links is generally inadequate. Consideration must be given to obtaining the maximum benefit from every component of the electrode system in order that economic designs may be produced which satisfy modern requirements. It is still convenient, however, to consider separately the various components of a complete system, and a preliminary grouping may be made as follows:

(i) Specific earth electrodes.
(ii) Fortuitous earth electrodes.
(iii) Interconnections.

(3.1) Specific Earth Electrodes

The specific earth electrodes are those parts of a station installation which are specifically designed to dissipate earth-fault currents. The majority of such electrodes are installed for this purpose alone, but some types which will be described, such as in large civil engineering works, are provided primarily for a different purpose, and their use as earth electrodes is a secondary feature of their design.

(3.1.1) Earth Plates.

Plates have been the traditional earth electrode for many years—in fact, the term 'earth plate' has tended to become synonymous with the term 'earth electrode'. Their outstanding advantage is their great current-carrying capacity, but this is frequently offset by their high dissipation resistance, especially in high-resistivity soils. Furthermore, the cost of excavation generally makes them uneconomical for large installations unless the soil resistivity is extremely low.[1–4]

The use of coke in conjunction with earth plates has frequently been recommended in the past as a means of obtaining low resistance values in high-resistivity soils. It is argued that the coke increases the effective area of the plate and thereby improves its conductance. Although this is undoubtedly true, the improvement is usually comparatively small and hardly warrants the increased cost of excavation.

(3.1.2) Small-Diameter Rods.

In recent years the use of small-diameter rods has become increasingly popular, the main advantage of rods being that they are easy and cheap to install, especially when driven by a portable electric hammer into soft ground. The length of rod and the number connected in parallel can be increased to obtain a given low resistance in restricted sites, but the current rating is rather low unless the rods are installed in soil of very low resistivity.[2, 4, 17] For large installations the number of rods will generally be governed by the current rating rather than by the dissipation resistance. The driven rod is most advantageous where a stratum of low-resistivity soil lies at some depth, and allows of advantage being taken of this to reduce the size of the installation.

With an electrode system consisting of a large number of rods the interconnections can be left bare in the ground, and for a very extensive installation the interconnections may provide most of the dissipation conductance. Schwarz has produced analytical expressions which deal with this aspect of design.[7]

(3.1.3) Pipes.

Large-diameter cast-iron pipes installed vertically were at one time popular as earth electrodes. They are, however, expensive to install, and although they have a good current rating they are not as economical for the same rating as the small-diameter rods preferred nowadays.

Smaller-diameter steel pipes ($1\frac{1}{2}$–3 in) are occasionally used where driving equipment is available on the site. Dissipation resistances are generally similar in magnitude to those for small solid rods, although the increased diameter does give a proportional increase in current rating owing to the larger surface area. Pipes have been successfully installed in sand and loose sandy soils by means of a high-pressure water pump coupled to the top of the pipe. The jet of water from the bottom swirls away the soil from beneath the pipe, rapidly boring a hole into which the pipe sinks. As the ground dries out after installation the soil packs around the pipe, giving a very efficient connection. At a sandy coastal site, 40 ft long pipes $2\frac{1}{2}$ in in diameter were installed by this method at the rate of one every 15 min.

(3.1.4) Metal Piles.

The interlocking steel piles frequently used in the foundation of large structures form an ideal earth electrode. Their great length and heavy section give a low dissipation resistance with high current-carrying capacity, whilst the cost of the piles themselves is not unduly high. Unfortunately, the installation costs can be very high and, unless a pile driver is already erected on a site, it is uneconomical to provide them purely as earth electrodes. Generally their use would be confined to cases where steel piles are required as part of the structural foundation work of the station.

For groups of piles forming part of a foundation, steel bonding strips of large cross-section should be welded between all the piles of a group. Where the piles are interlocked to form a curtain or retaining wall, connection should be made to a steel strap which is welded across at least six of the piles in the wall. In addition, adjacent piles should be welded together for a further distance of at least five yards on either side of the connection point.

(3.1.5) Concrete Piles.

Where the soil resistivity at a site approximates to that of concrete (roughly 20 000 ohm-cm), the reinforcing of buried concrete structures will be effectively in contact with the earth. The use of reinforced concrete piles for foundations is quite common, and, wherever practicable, advantage should be taken of incorporating their metalwork in any earth-electrode system to be provided. The dissipation resistance should be good, but the current rating is rather uncertain and probably approximates to that of the reinforcing rods by themselves. It should be noted that prestressed concrete piles are generally not suitable for this service, owing to the small-diameter wires used for reinforcing, which may be damaged by fault currents, thus impairing the strength of the piles.

The most satisfactory method of making a good electrical connection to reinforced concrete piles is to select suitable bars in the foundation raft supported by the piles and to weld these bars to form a continuous conductor adjacent to all the pile heads, this bar then being welded to the ends of the pile reinforcements. Where the outgoing connection is to be made, a copper strap long enough to reach clear of the foundation should be welded to the interconnecting bar, the junction of the two metals and the length of copper being completely sealed with bitumen or a similar impervious medium. All these interconnections must, of course, be made when the reinforcing is laid and before the concrete is poured to complete the foundations.

(3.1.6) Strip Electrodes.

It is one of the basic principles of the design of earth electrodes that the larger the area covered by a given amount of material, the more efficient is the electrode from the point of view of dissipation resistance. Thus a long strip makes efficient use of material, but there is a limit to the amount that such a strip

can be stretched out. Current-carrying capacity and longitudinal resistance give a minimum permissible cross-section which practice has shown to be about 1 in × $\frac{1}{8}$ in for copper or 2 in × $\frac{3}{16}$ in for steel, whilst consideration of the a.c. (power-frequency) impedance gives a critical length beyond which no appreciable reduction in dissipation resistance is obtained.[11] For normal-sized strips this critical length is approximately 100 yd. The current rating of strip electrodes is high, but the cost of installation can also be high and a large clear area is generally required.

(3.1.7) **Mesh Electrodes.**

A variation of the strip-electrode system is one in which strips are laid in a mesh formation covering the whole of the site, the strips being connected together at all intersections. The density of the mesh can be varied from a minimum of one strip around the circumference of the site to a maximum of a solid plate covering the whole area. Schwarz has developed formulae for the dissipation resistance for such mesh electrodes,[7] a simplified version of which is

$$R = \frac{140}{\sqrt{A}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

for a soil resistivity of 10 000 ohm-cm, where R is the dissipation resistance of a solid plate covering the whole of a site A square feet in area.

There is little doubt that a mesh electrode is one of the most efficient designs possible, since it gives maximum usage of the site area, a minimum of material, uniform voltage over the whole area of the station site and, generally, low dissipation resistance. The practical difficulties which have prevented this system from achieving greater popularity are the necessity for obtaining access for excavation work over the entire site area and the cost of installation occasioned by the large amount of jointing.

For outdoor substations a large amount of interconnecting metal is required for the earthing of structures and items of plant, and if consideration is given to the problem in the early stages of design it is possible to make use of this material to achieve a layout which is virtually a mesh electrode covering almost all the available space.

(3.1.8) **Earth Wires.**

Where continuous earth wires are installed on overhead lines and are earthed at every tower or pole, they can help to reduce the dissipation resistance of an earth-electrode system if they are bonded to it. Unfortunately, the reactance of earth wires is quite considerable, limiting their usefulness in large installations.

(3.2) Fortuitous Earth Electrodes

Fortuitous earth electrodes are metallic components of an installation which are not designed as earth electrodes but form an alternative path for fault currents. Owing to their comparatively high resistance, these connections do not normally carry currents liable to cause damage, but cases do occasionally arise which require special treatment, and fortuitous connections should never be dismissed as unimportant.

(3.2.1) **Cables.**

Cables form the largest chance earth electrode in many stations. The majority of cables are protected by jute servings which give a small amount of insulation when new, but when saturated and decayed the metal sheathing or armouring becomes effectively in contact with the soil. The more common use of p.v.c. and other impervious outer sheathings to minimize corrosion is eliminating the effectiveness of cables as earth electrodes. The dissipation resistance of cables actually in contact with the ground would be similar to that for strip electrodes of comparable dimensions, although it is difficult to make allowances for servings.

(3.2.2) **Water Pipes.**

Pipes forming part of a station installation may be deliberately used as earth electrodes and in many cases will tend to equalize potential gradients within the station. The connection of town water-supply mains to a station earth electrode should, however, be treated with care. It is desirable that pipework inside a station should be bonded to the station earth to avoid possible high contact potentials, but the transfer of large currents and high potentials away from the station is equally undesirable. Wherever possible, asbestos cement or similar insulating material should be used for the service connection of a water main to minimize these problems.

(3.2.3) **Structural Earths.**

A large amount of metalwork is involved in most civil-engineering works, including the frames of buildings, the reinforcing of concrete, piers, caissons, cooling water pipes, etc. This steelwork can be bonded to the earth-electrode system deliberately, but in any case some fortuitous contact is certain to exist.

The current rating of these structural earths is problematical, and care should be taken if it is intended to rely upon them to any great extent. A possibility which must be considered is the drying out of the soil, which can occur under structures of large area, thus invalidating measurements made during construction.

(3.3) Interconnections

The miscellaneous earth bonds and interconnections which are fixed to structures, laid in trenches and laid direct in the ground form one of the most important parts of an earth-electrode system, connecting together all the main earth electrodes, providing a basic earth bond for every piece of equipment in the station and frequently providing as much as one-quarter of the total dissipation conductance.

As mentioned in Section 3.1.7, it is often possible to design the interconnections deliberately to form the main station earth-electrode system.

Where electrically connected stations are in close proximity it is generally desirable to provide a definite earth bond between them; similarly, separate sections of a large installation require interconnecting. These interconnectors should not have a cross-section smaller than that of the main earth busbar, and should preferably be laid bare in the ground to take advantage of the extra dissipation conductance they can contribute.

Where main cables exist between sites, these will frequently provide an adequate bond, and the provision of further connections can generally be justified only where they will assist appreciably in reducing the dissipation resistance. It is desirable to divert fault current away from cable sheaths if possible, but in the case of large power cables the cross-sectional area of their sheaths is such that it is only practicable to provide effective shunts over short distances.

(4) BASIC PRINCIPLES OF DESIGN

An essential preliminary to the design of an earthing system is an examination of the proposed station layout, site surveys, borehole details, water table, structural details, etc., to determine any possible natural or constructional features which could be turned to advantage or which would impose limitations on the design. A detailed survey of soil resistivity should be made over the whole site, attention being given to points indicated by the preliminary examination. Knowing the soil resistivity it is possible to make a rough estimate of the efficiency of electrodes

which may be inherent in other site works, such as cooling-water ducts, piling, etc., and to determine what additional electrodes are required. The basic layout of the main earth busbar should be determined at an early stage of the design, and the type and siting of additional electrodes determined by this layout and the site conditions.

circulating water plant, piles and the main buildings, backed up occasionally by isolated electrodes.

Table 1 gives details of the earthing installations at a number of generating stations of various ages and designs, and one of these is further described in detail in the Appendix as a typical example of a modern installation.

Table 1

Details of Earth Electrode Installations at Generating Stations

Generating station	Installed capacity	Approximate installation date	Average soil resistivity	Nominal earth electrode	Dissipation resistance	Maximum earth fault current
	MW		ohm-cm $\times 10^3$		ohms	kA
A	17·5	1923–29	4–6	Plates and pipes	0·04	2·5
B	80	1925–48	0·9–1·3	Cooling water pipes and rods	0·01	2·4
C	360	1952–57	0·6–1·0	Steel piles	—	9·0
D	80	1925–43	0·3–1·0	Plates	0·04	6·8
E	155	1925–42	1–2	Cooling water pipes and plates	0·03	8·0
F	120	1943–51	5–15	Cooling water pipes and plates	0·16	0·75
G	155	1931–44	10–96	Plates	0·03	7·8
H	345	1953–57	20–45	Pumphouse caisson and steel piles	—	8·0
J	25	1923–28	1–5	Rods	0·03	1·5

As mentioned previously, one of the basic principles of design is to spread the earth electrodes over as much of the site as possible, in order to obtain maximum efficiency and also to avoid large potential gradients within a station site. It is desirable to maintain adequate spacing between adjacent electrodes, to avoid overlapping of effective resistance areas and so achieve the minimum dissipation resistance.

It was common practice in the past to provide a separate earth-electrode system for each section of the main equipment, as many as six or seven systems being found in some power stations. These would nominally be separate, but under fault conditions obscure interconnections might become apparent. Such conditions are not tolerable where very large fault currents are possible.

It is generally impracticable to obtain small isolated electrodes which are satisfactory for the very heavy duties being considered, but there are, in addition, a number of other reasons for insisting that wherever possible all the earth connections of a complete installation should be bonded together. With this arrangement the station as a whole becomes almost an equipotential area under earth-fault conditions, and this eliminates most problems concerning shock due to accidental contacts. The boundary of this equipotential area can be clearly defined and adequately protected, and all services entering the site can be satisfactorily dealt with. Another merit of the integrated system is that earth faults which occur on station equipment have their neutral return circuit completed without leaving the metallic earth conductor, thereby eliminating many of the dangerous potential gradients which could arise under these conditions with the old arrangement of separately earthed neutrals.

(5) EXAMPLES OF EARTH-ELECTRODE SYSTEMS

(5.1) Generating-Station Earth Systems

The design of earthing systems for generating stations is usually characterized by the availability of an extensive site, large buildings, massive plant and the construction of comprehensive civil works. High earth-fault currents are very common in modern installations, but the design of the earthing equipment is generally not too difficult owing to the extensive nature of the works. The main electrodes can often be formed by the

(5.2) Substation Earth Systems

The design of earth-electrode systems for substations is usually more difficult than for generating stations, mainly owing to the restricted site area, the absence of major civil works, and fault currents which are frequently as high as those encountered at the generating stations. It is generally necessary to take advantage of all the available site and to approximate as closely as possible to a mat of metal covering the whole area. Owing to the concentrated nature of the earth system, steep potential gradients are a definite possibility in the vicinity of site boundaries, and the provision of grading conductors in the ground near fences may sometimes be necessary.

Plates have frequently been employed as electrodes in substations and where the soil resistivity is low prove quite satisfactory. With large prospective fault currents they are, however, generally unsatisfactory for high-soil-resistivity conditions, and rod, strip or mesh electrodes are generally used as alternatives. It is rarely possible to achieve a satisfactorily low dissipation resistance with the primary electrodes alone, and every advantage must be taken of the possible conductance of structural earths when available, earth busbars, cables, earth wires, etc.

Table 2 gives details of a number of typical 132 kV substation earthing installations, two of which are described more fully in the Appendix.

(6) MEASUREMENT OF DISSIPATION RESISTANCE

The dissipation resistance can be taken as the criterion of the efficiency of an earth-electrode system, such factors as current-carrying capacity and impedance to steep-fronted waves generally being almost impossible to determine. The measurement of dissipation resistance must be made with reasonable accuracy, in order that erroneous conclusions shall not be drawn from the results, but when it is realized that, for a prospective earth-fault current of 15 kA, a resistance of 0·1 ohm would generally be considered too high, it becomes obvious that such measurements present their own difficulties.

(6.1) Earth-Testing Ohmmeter

The earth-testing ohmmeter, which is also used for the measurement of soil resistivities, is the instrument most commonly used for the measurement of dissipation resistance, and

Table 2

DETAILS OF EARTH-ELECTRODE INSTALLATIONS AT SUBSTATIONS

Substation	Transformer capacity	Approximate installation date	Average soil resistivity	Nominal earth electrode	Dissipation resistance of nominal electrode	Dissipation resistance of complete installation	Maximum earth-fault current
	MVA		ohm–cm $\times 10^3$		ohms	ohms	kA
K	60	1939	5–8	Plates	—	0·21	2·5
L	120	1954	4–8	Strip	0·34	0·08	6·0
M	135	1954	10–20	Strip	0·8	0·3	8·0
N	180	1938	6–20	Plates	—	0·16	6·0
O	90	1955	5–10	Plates, strip and concrete piles	2·0	0·15	4·0
P	90	1954	25–30	Strip	—	0·28	6·0
Q	60	1954	10–20	Rods	1·5	0·3	6·2
R	285	1954	2–10	Steel piles	0·4	0·2	8·0
S	135	1941	9–13	Plates	—	0·03	7·8
T	90	1956	100–200	Large steel building	0·15	—	8·0
U	90	1951	2–3	Plates	1·7	0·07	6·5
V	60	1955	20–50	Rods	2·0	0·9	3·3
W	30	1954	6–10	Rods	2·4	0·6	1·5

has frequently been described in great detail.[4, 15, 16] Its simplicity and portability make it invaluable for the testing of all small earth electrodes, but for extensive installations, with their very low dissipation resistance, a number of inherent weaknesses tend to make the earth-testing ohmmeter unsatisfactory.

These disadvantages arise mainly from the use of the equipment at the extreme end of its designed range, and discretion is necessary when measuring the dissipation resistance of an electrode system where a value of less than 0·3 ohm is expected. In addition, the earth-testing ohmmeter does not measure the true a.c. impedance of an electrode system having appreciable reactance.

(6.2) Geophysical Earth-Testing Ohmmeter

The geophysical earth-testing ohmmeter is a modification of the standard equipment developed for geophysical surveys using soil-resistivity values (Fig. 2). Its use for the measurement of

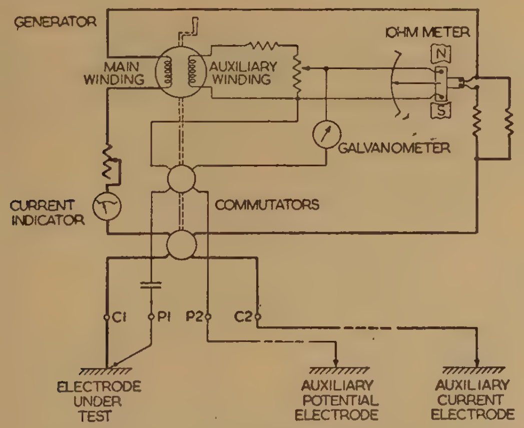

Fig. 2.—Circuit diagram for geophysical earth-testing ohmmeter.

low values of dissipation resistance avoids some of the difficulties mentioned in the previous Section. A potentiometer circuit used with a galvanometer permits greater overall sensitivity, giving a full-scale deflection on the bottom range for 0·3 ohm. The generator is separately mounted, which avoids the mechanical vibration associated with its operation, but possible errors due to faulty commutation in the presence of large stray potential fields may still occur, and the incorrect measurement of reactive systems also remains.

(6.3) Alternating-Current Injection

A general alternative to the use of the earth-testing ohmmeter is the injection of alternating current, and in the simplest and most commonly used form, a 50 c/s a.c. source, usually a transformer, is connected to the electrode to be tested and to the auxiliary current electrode; the current is measured with an ammeter, and potential differences are measured with a high-impedance voltmeter.

The great merits of this method are the simplicity of the equipment required, the fact that the results are obtained at the operating frequency, thus eliminating any errors due to components of the electrode system having large reactance, and the availability of a large test power.

There are, however, a number of disadvantages:

(*a*) In the early stages of construction work, power supplies are not always available at station sites.

(*b*) A high-impedance voltmeter is necessary to avoid errors due to the resistance of the auxiliary potential electrode.

(*c*) Interference from stray potentials in the ground can be quite considerable, and unless special circuits are used completely false readings can be obtained. The use of a large test current will minimize these errors, but large test currents are not easily achieved and the expense of installing a special temporary current electrode may be quite considerable.

Several variations on this testing technique have been devised in an attempt to eliminate such disadvantages, and three of these variations are described in the following Sections.

(6.3.1) 30 c/s Alternating-Current Injection.

The E.R.A. has developed a method which uses an a.c. source of frequency close to the system frequency, but with sufficient separation to permit of the design of filter networks to differentiate between them.[10] The frequency of 30 c/s was chosen as being suitable, the test current being supplied from a battery-powered motor-generator.

A valve voltmeter, which is preceded by an amplifier tuned to accept 30 c/s voltages and reject 50 c/s voltages, is used for the measurement of the potential drop in the test circuit.

This equipment is reasonably free from interference due to stray ground potentials and can be satisfactorily operated with a small test current.

(6.3.2) 3-phase A.C. Injection Method.

The sources of interference which make the simple 50 c/s injection method inaccurate are induced potentials due to

coupling between the current and potential circuits, electrolytic potentials and 50 c/s and harmonic potentials due to stray currents in the ground. The induced potentials can be minimized by suitable choice of routing for the test leads, and the electrolytic potentials can be blocked by the introduction of a capacitor into the measuring circuit. The elimination of the effects of stray currents is, however, more difficult, but, if it is assumed that sinusoidal potentials of the fundamental frequency predominate and remain reasonably constant in magnitude and phase, it is possible to determine their effect by altering the phase angle of the test current.

A simple way of doing this is to derive the test current from one phase of a 3-phase supply, measurements of potential being made using each phase in turn. The stray potential should be measured again, without the test current. From these results it is possible to determine what the true potential would be in the absence of stray fields. This determination is indicated in Fig. 3, based on the assumptions previously mentioned, which

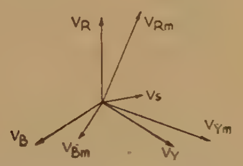

Fig. 3.—Vector diagram showing relationship of voltages for 3-phase a.c. injection method of measuring dissipation resistance.

V_R, V_Y and V_B = Required voltage drop due to test current.
V_s = Stray ground voltage.
V_{Rm}, V_{Ym} and V_{Bm} = Actual measured voltages.

$$V_R = \sqrt{\left(V_{Rm}^2 - V_s^2 - \frac{2V_{Rm}^2 - V_{Bm}^2 - V_{Ym}^2}{3}\right)}$$

$$V_Y = \sqrt{\left(V_{Ym}^2 - V_s^2 - \frac{2V_{Ym}^2 - V_{Rm}^2 - V_{Bm}^2}{3}\right)}$$

$$V_B = \sqrt{\left(V_{Bm}^2 - V_s^2 - \frac{2V_{Bm}^2 - V_{Ym}^2 - V_{Rm}^2}{3}\right)}$$

have been found in practice to apply sufficiently well to the majority of sites.

Where large test currents are used, as is always desirable, the necessity for a 3-phase supply is an inconvenience, and the following method was developed in an attempt to eliminate this requirement and also to simplify the analysis of results.

(6.3.3) **A.C. Potentiometer Method of Measurement.**

Fig. 4 indicates a typical vector relationship for a single-phase a.c. resistance measurement where the effect of induction and

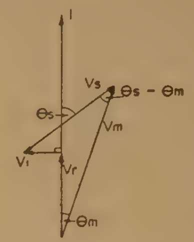

Fig. 4.—Vector diagram showing relationship of voltages for a.c. potentiometer method of measuring dissipation resistance.

I = Test current.
V_r = Desired voltage drop due to I through dissipation resistance.
V_i = Induced voltage from test leads.
V_s = Stray ground voltages.
V_m = Actual measured voltage.

stray potentials is taken into account. It can be seen that, if the magnitudes and phase angles, relative to the current, of the stray potential and the measured potential are known, it is possible to determine the required value by simple geometry. A simple form of a.c. potentiometer, as shown in Fig. 5, may be used to make the measurements.

In difficult situations where large stray potentials exist, this potentiometer method has proved extremely sensitive with good discrimination against interference.

(7) MEASURING TECHNIQUES

Although the choice of testing methods and equipment is of great importance in the search for accuracy when making dissipation-resistance measurements, the use of suitable measuring techniques in the field is equally important. It is proposed to discuss the various aspects of measuring techniques as they would arise during an actual test.

(7.1) Choice of Measuring Points

Where a self-contained ohmmeter is used, the point of current injection and the reference point for potential measurements are

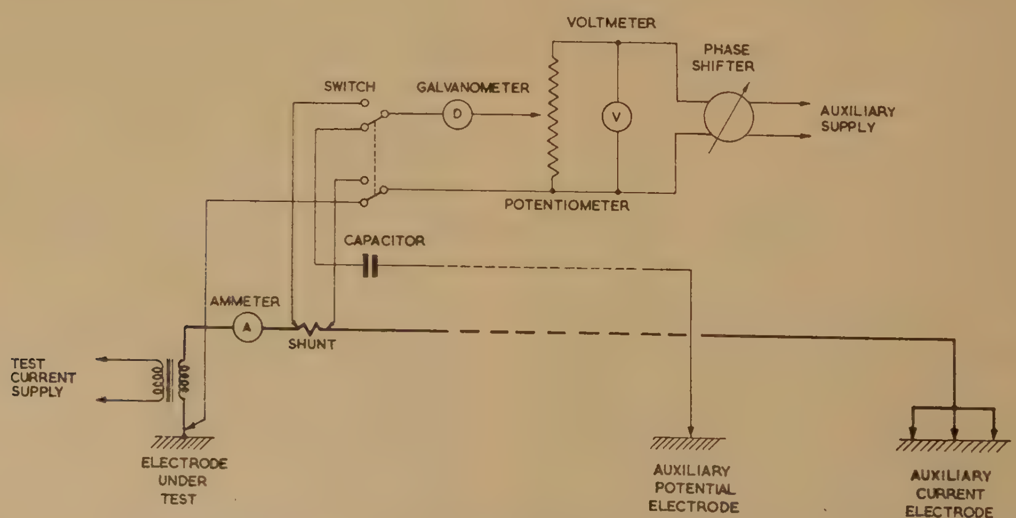

Fig. 5.—Circuit diagram for a.c. potentiometer for measuring dissipation resistance.

the same. The usual practice when using an earth-testing ohmmeter is to have a common connection for current and potential circuits from the instrument to the earth busbar. Where very low values of dissipation resistance are being measured this method is unacceptable and a separate potential connection must be used.

When using 50 c/s a.c. injection methods, the current connection to the earth busbar is usually already fixed, being generally the neutral connection of the transformer supplying the test current.

Where a large test current is being used at an extensive site, the voltage drop in the earth busbar can be appreciable, and measurements of potential should be made to ensure that errors due to this are not introduced.

Whatever method of measurement is used, it is wise to avoid making the test connection to an extremity of the earth system, as the possibility of false measurements arises, owing to high-impedance connections, voltage drop due to heavy current, etc. It is desirable to site the measuring point in the vicinity of the major source of earth-fault current.

(7.2) Auxiliary-Current Electrode

One of the more difficult parts of the test procedure is the provision of a suitable auxiliary-current electrode. The impedance of the auxiliary electrode and its connecting lead generally imposes a limit on the attainable accuracy whatever method of measurement is used, and it is desirable to reduce this impedance to a minimum. Where high soil resistivity is encountered, it can be extremely difficult to obtain a reasonable dissipation resistance for the auxiliary electrode, and the saturating of the electrode area with salt solution sometimes provides a satisfactory answer. A convenient design of auxiliary-current electrode is described in the Appendix.

It is essential that the resistance areas of the auxiliary-current electrode and the electrode system under test should not overlap, and, in the case of large installations, this involves a long connecting lead for the auxiliary electrode. Experience has shown that this electrode should be at a distance of at least 4–5 times the longest diagonal of the site, assuming the electrode system to be evenly distributed over the whole of the site. On some occasions even this spacing has been inadequate, owing to the distortion of current distribution by railway lines, cables and other conductors in the ground.

Little is gained by using large-section conductors for the connection to the current electrode, since the current flow is controlled to a large extent by the inductance; it is preferable to work the conductor at the maximum-possible current density. The maximum length which can be drawn out in one stage from the test point is about 600 yd. This corresponds to a maximum site diagonal of 150 yd, which is sufficient for the majority of substations but too small for the large power stations where sites of at least 300–400 yd long are encountered.

For these occasions the desirable alternative is to obtain access to some suitable power circuit which can be earthed at a considerable distance, preferably at another station. A current circuit is then obtained which has adequate current-carrying capacity, a satisfactory auxiliary electrode and the added advantage that it permits tests to be carried out at both stations simultaneously if this is desired.

(7.3) Auxiliary Potential Electrode

The earth-testing ohmmeter is calibrated for an assumed value of resistance for the potential connection and, while this value is by no means critical, it is desirable to check the resistance and make corrections if necessary, especially in conditions of very high soil resistivity. The low-resistance version of the standard

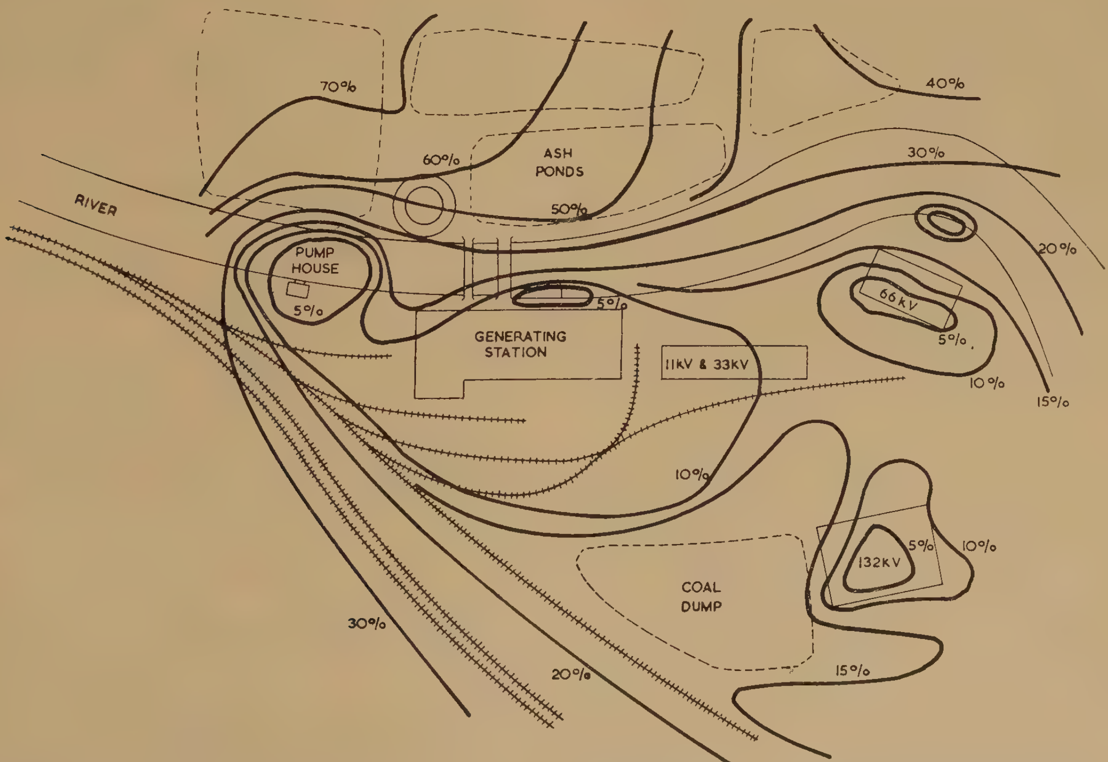

Fig. 6.—Diagram of equipotentials in neighbourhood of generating station E during earth-fault conditions.
Percentages given are of total voltage drop in earth-electrode system.

equipment is provided with an adjustable compensating resistance to eliminate the effect of variations in potential electrode resistance. Where a high-impedance detector is used, such as a valve voltmeter, the resistance of the potential circuit can generally be neglected.

As mentioned in the previous Section, the distances involved when taking measurements at large stations can be considerable, and it is sometimes almost impossible to obtain by normal methods measuring points sufficiently far from the station to ensure the inclusion of the majority of the resistance area. In these cases a telephone line earthed at a considerable distance to give a reference earth potential is a satisfactory solution.

(7.4) Measuring Procedure

For large installations it is never sufficient to determine dissipation resistance by only one measurement. There are so many factors which can affect potential distribution that even in the simplest of cases it is necessary to take a series of readings with the potential electrode being moved successively farther and farther from the system under test. At least two such lines of tests should be made, the first being in the direction of the auxiliary-current electrode, the second being preferably in the opposite direction or at least 90° from the current lead. The first set of results will indicate if the auxiliary-current electrode is at a sufficient distance, although these results may be affected in magnitude by inductive interference from the current lead.[11] The second set of results will give a more correct value for the potential gradient.

In the case of the larger and more complex installations, and even for the smaller sites when time and labour allow, it is desirable to make a complete survey of the potential distribution in the vicinity of the station. Provided that the total voltage drop in the dissipation resistance of the electrode system is known, such as by comparison with a reference earth potential obtained via a telephone line, it is rarely necessary to carry out a detailed survey to a greater distance than that corresponding to 50% of the total voltage drop.

Fig. 6 shows the equipotential diagram obtained for a large generating station (station E). The effect of the various electrodes and buildings can be seen and the potential distribution around the small pump-house up-river from the main station should be noted. This pump-house belonged to an independent water authority although situated within the station boundary, and was coupled to an extensive system of cast-iron water mains. The connection between it and the station earth system was originally quite fortuitous and was discovered by the plotting of the system of equipotentials. The distortion caused by railway tracks and ash dumps is noticeable, and it can be appreciated that isolated measurements could give false results if they were taken in the wrong direction.

(8) CONCLUSIONS

Where high earth-fault currents are likely to occur and the soil resistivity is high, the designing of satisfactory earth-electrode systems presents many difficulties, and it is essential to make use of every possible connection with the ground in order to obtain the low dissipation resistances required by present-day practice. The design principles recommended apply equally to areas of low soil resistivity, where economies in the use of material could be made by paying greater attention to earth system design. For example, it is frequently possible to use the main earth busbar to form a mesh electrode, thereby eliminating the provision of isolated electrodes, which are generally expensive and, in a depressingly large number of cases, contribute little to the conductance of the earth-electrode system.

It may be thought that the methods of earthing used in the past have been sufficiently proved and could well be extended to meet the increased stresses. A close examination of the earthing conditions at old stations, however, has revealed how unsatisfactory such a policy would be. The general practice in the past has been to install an arbitrary number of quite small electrodes which were generally not related to the plant design and the soil resistivity but were sufficiently good for the limited plant capacity originally installed. Where large increases in fault level have occurred dangerous conditions can arise, and in some cases actual damage has been caused to station equipment by earth-fault currents. The fact that this has not occurred frequently is usually explained by the low dissipation resistance fortuitously provided by the general mass of metal in a station. Fault levels have now risen to the point where these casual electrodes are no longer satisfactory, and it is essential to plan the station earthing (including future extensions) with nearly as much care as is devoted to the primary connections, in order to obtain adequate designs in the comparatively restricted space of modern sites.

The measuring techniques used in the past have generally not given consideration to the special problems of the large installations and have tended to give results which are not repeatable. The low values of resistance to be measured and the large areas to be covered tend to introduce discrepancies into the testing procedure which give rise to the position where major design work can be and has been based upon incorrect measurements.

It is hoped that the paper will attract attention to the special problems of earth-electrode design for very high fault currents, and that further research will be stimulated in this field of engineering.

(9) ACKNOWLEDGMENTS

The author wishes to thank the Central Electricity Authority and especially Mr. H. J. Bennett, Divisional Controller, South Wales Division, for permission to publish the majority of the information contained in the paper. He also wishes to acknowledge the permission received from Evershed and Vignoles Ltd. to publish certain information and diagrams.

The preparation of the paper could not have been undertaken without the assistance of the author's colleagues, and he wishes to thank them all for their help and criticism.

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(11) APPENDIX

(11.1) Earthing System at a Large Coastal Generating Station (Station H)

Station H has an installed capacity of 345 MW generating at 132 kV through direct-connected 11/132 kV step-up transformers. It is a coastal station using sea water for cooling. The entire site is of sand over a deep rock substratum, the average sand resistivity being 40 000 ohm-cm, and the normal water level is at an average depth of 20 ft. The main station structure is completely supported on piles and the pump-house is surrounded by a steel caisson. The 132 kV switch-house is a separate building and is erected on a cellular raft which 'floats' on the sand. Fig. 7 shows the main earth system for this station.

The piles beneath the main buildings are all of reinforced concrete, the average dissipation resistance for one pile being 2 ohms. There are 5 500 piles in the complete foundation, and although they have not been considered as a primary earth electrode, they have been thoroughly bonded to the main structural steelwork as an adjunct to the main system. The foundations for the main transformers are supported on 70 ft steel box piles which are connected together in groups to form a series of large electrodes along the full length of the south wall. These steel piles have an average dissipation resistance of 0·5 ohm, and there are a total of 200 installed. Owing to their close grouping for structural reasons, the electrical paralleling efficiency is poor.

The steel caisson of the pump-house is used as another primary earth electrode and is bonded to the main station earth.

In view of the very high soil resistivity, it was considered that reinforced concrete would probably make as good an earth connection as a direct metal one, and the 132 kV switchhouse foundation was therefore modified slightly with the intention of using it as an electrode. Junctions in reinforcing bars were welded and a large number of the reinforcing bars were welded to the main building steelwork to which the earth busbar was fixed. This concrete-raft foundation had a dissipation resistance of 0·2 ohm, but, in view of the experimental nature of the electrode, eighteen 40 ft pipes were installed by the water-jet method as additional back-up electrodes.

The generating station is not yet complete and it has not been possible to carry out complete tests on the installation, but measurements made to date indicate a probable dissipation resistance for the whole earth system of less than 0·05 ohm. In view of the prospective maximum earth-fault current of 8 kA, it can be seen that the dissipation resistance obtained is no more than adequate, despite the very extensive nature of the earth system.

(11.2) Details of Substation Earthing Systems

(11.2.1) Substation R.

Substation R, with 21 circuits and a fault level of 3 500 MVA at 132 kV, was built on soft ground of low resistivity, the average

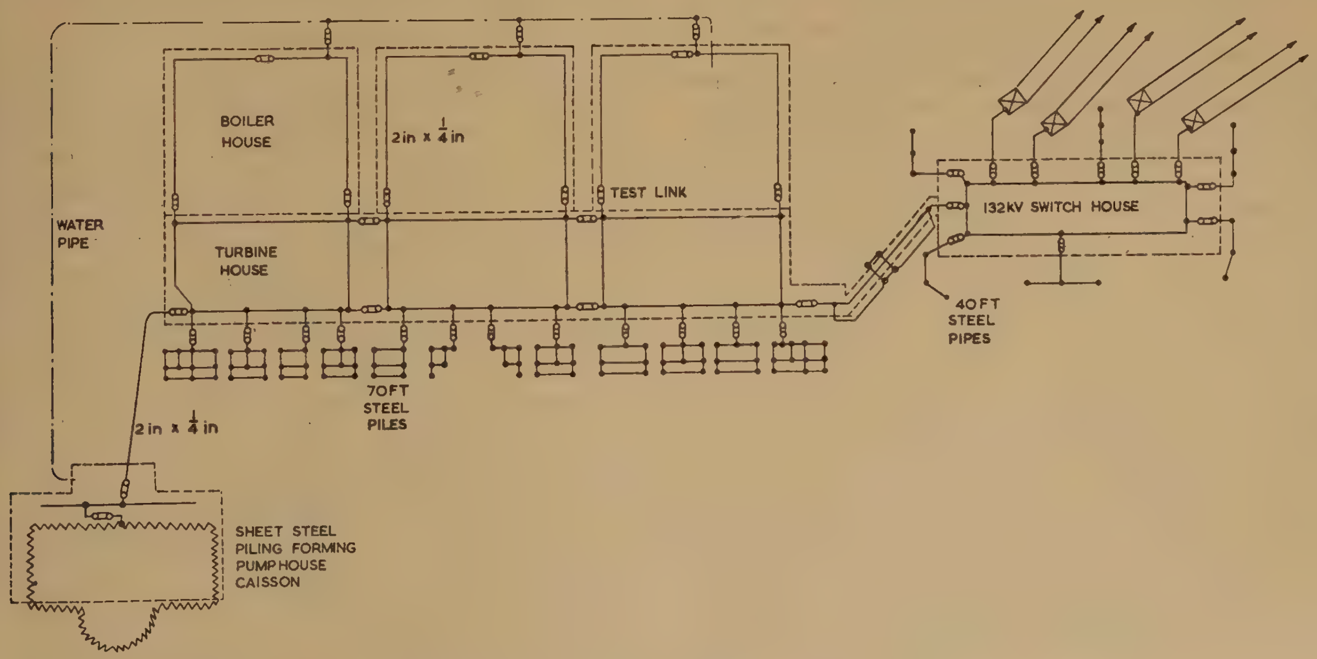

Fig. 7.—Layout of main earth system at generating station H.

being 6000 ohm-cm. All the structures are built on piles, but being of the prestressed type, they were considered unsatisfactory for use as earth electrodes. The presence of pile drivers on the site was turned to advantage and 14 steel piles were driven, at small cost, to act as the main earth points. These

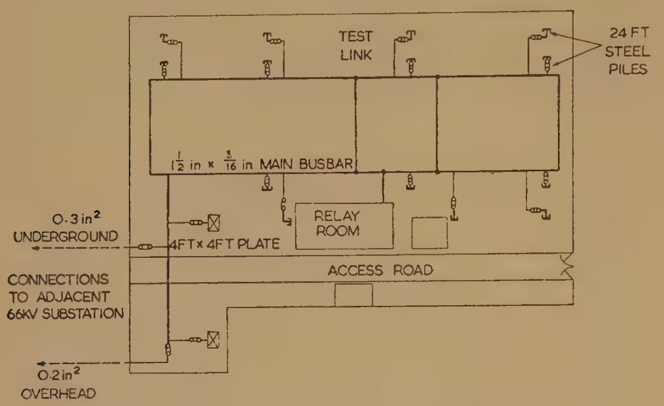

Fig. 8.—Layout of earth system at substation R.

piles are distributed uniformly over the site (Fig. 8) and their average dissipation resistance is 5 ohms.

A lower-voltage substation, 300 yd away, is connected to the main substation by a 66 kV overhead wood pole line and by underground control cables. The earthing systems of the two stations are bonded via a $0\cdot2\,in^2$ copper earth wire strung above the 66 kV line and by two $0\cdot175\,in^2$ conductors laid bare in the ground along the cable route.

(11.2.2) **Substation P.**

The 132 kV substation P was built on a bleak mountain top on boggy soil which would appear to provide the possibility of an ideal low-resistance earth system. However, the high annual rainfall and continuous run-off of water wash the majority of salts out of the soil, leaving it of high resistivity despite its being perpetually water-logged. Extensive drainage was required at this site and $0\cdot1\,in^2$ stranded copper conductor was laid at the

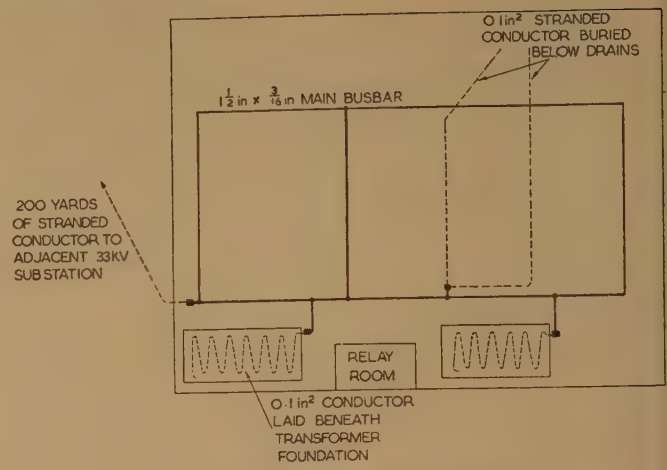

Fig. 9.—Layout of earth system at substation P.

bottom of each trench beneath the porous drains, giving a total dissipation resistance of 2·2 ohms (Fig. 9). Two further electrodes were made by zigzagging a length of the $0\cdot1\,in^2$ conductor beneath each transformer foundation before the concrete was poured, and these electrodes had resistances of 2·8 ohms and 3 ohms. A 200 yd run of 33 kV cables connects this substation to an adjacent 33 kV substation, and a stranded copper conductor of $0\cdot2\,in^2$ cross-section was laid in the trench with the main cables as an additional bond between the two stations.

(11.3) **Suggested Design for Auxiliary-Current Electrode**

A series of 2 ft long ¼ in diameter rods, which can be driven and withdrawn with light hand tools, should be connected together in groups of 10 by a flexible conductor, the spacing of the rods being 3 ft. The number of groups used can be adjusted to suit the soil resistivity, as many as 8–10 groups being used in difficult conditions. Even these large numbers give an electrode only 10 yd square, the dissipation resistance obtained being low. The groups of rods when packed are quite compact, and if they are made of aluminium one man can carry large numbers.

DISCUSSION BEFORE THE SUPPLY SECTION, 27TH MARCH, 1957

Mr. L. Gosland: Since much of the early electric supply in this country was in regions of high soil conductivity, connection with earth was achieved without much difficulty, and normal practice was based on the use of the earth as a reasonably good conductor. Extension of distribution into rural areas soon brought difficulties, and the earthing of distribution systems has been much discussed. The present paper shows that the same difficulties arise with large stations, and that the practice now is, as it should be, to take account of earthing requirements at the commencement of design, so that all useful electrodes inherent in the construction make a proper contribution and the need for special electrodes is minimized.

The paper forms a very useful review of the subject and, not unreasonably, is entirely qualitative, referring to the literature for information on the characteristics of earth electrodes. There are, however, some data which the author should supply. It is stated that the design criterion for a satisfactory earth electrode is that the voltage rise during an earth fault should not exceed 430 volts, the limit above which special provisions are required for incoming Post Office cable, and that if this limit is not exceeded, the electrode will be satisfactory in all respects from the point of view of safety. It is nevertheless clear that in some cases this limit is exceeded. What criteria does the author then apply? Some indication is also required of the manner in which the earth-fault current is calculated. The earth-fault current at a point is not necessarily the current flowing into an earth electrode at that point. Does the author make full allowance for interconnections, or does he, for example, allow for the possibility that one earth wire may be broken? Finally, in assessing the current-carrying capacity of electrodes, for how long is the fault assumed to persist? If the voltage is kept below 430 volts, and the duration below 1 sec, there is very little likelihood of damage to an electrode as such from excess current transfer to the earth.

The paper gives useful clear guidance on the use of steel reinforcement in concrete as an earth electrode. This practice need not necessarily be restricted to cases where the soil has resistivity comparable with that of concrete, although it is in such cases that it is most useful. The resistivity of concrete can range from below 8000 ohm-cm to above 100000 ohm-cm, according as it is saturated or very dry. The figure of 20000 ohm-cm suggested is reasonable for concrete in contact with moist soil. Inquiries made by the E.R.A. some years ago failed to elicit any case of damage to concrete by passage of fault current from steelwork embedded therein.

The advantages of the mesh-type electrode are stressed. It has some disadvantages, particularly that it may be near the surface

of the soil and consequently may have an unexpectedly high resistance in a very dry season. Like the strip electrode, it may have its most useful application where deeper electrodes are not practicable because of rocky subsoil. It may be useful to mention that the value given by Schwarz's formula, quoted by the author, for the resistance to earth of a plate covering the whole of an area, is closely approached when the plate is approximated by a net comprising as few as 16 meshes of conductors of practical size.

The author mentions a lack of information on the short-time current-carrying capacity of earth electrodes. There is in fact a considerable volume of data, described in his Reference 3 and in earlier E.R.A. reports. It is not practicable to calculate from first principles the short-time current-carrying capacity of any electrode in any soil, but where information is lacking, limiting specific loadings can readily be determined by simple tests on small electrodes, and used in practical design. There is thus some scope for the further basic investigations on earth electrodes which the author proposes, but the field is rather limited.

Dr. G. F. Tagg: One major factor in the design of earth electrodes is the soil resistivity, and I think the author should have emphasized this more than he has. If this is measured by the usual 4-electrode method using the formula for homogeneous soil, it is usually found that the value obtained varies with the electrode separation and the location of the test. This is, of course, due to the fact that the soil is never homogeneous, and with such variations in the measured value, the question then arises as to the correct value to take for the design. Work on this problem is in hand at the present time and some information may be available a little later.

An earth-testing ohmmeter is available, apart from the special geophysical one, which enables resistances lower than 0·3 ohm to be measured. The special instrument was, as its name implies, designed for large-scale measurements of earth resistivity. When used for earth-electrode measurements, the lower frequency of commutation and the light galvanometer may mean that with large stray potentials in the earth, it is difficult to obtain a satisfactory balance.

Another point concerns the arrangement of the auxiliary electrodes used in making the measurement, no matter what instrument is used. Mr. Humphries emphasizes the importance of a low current-electrode resistance in order to pass sufficient current. This is desirable for another reason. Suppose, for example, that the earth electrode under test has a resistance of 0·1 ohm, and that an accuracy within 5% is required. This means that the potential electrode must be placed sufficiently far away to include 95% of the resistance area, and this is not usually too difficult. However, for the accuracy required, the error in the measurement must not exceed 0·005 ohm. That part of the current-electrode resistance that is outside the potential electrode is included in the measurement, and so this should not exceed 0·005 ohm. If the current electrode has a resistance of 10 ohms, then only 0·05% of its resistance may be included, and the distance between potential and current electrodes becomes very great. If the resistance of the current electrode could be reduced to 1 ohm, then the portion which may be included is 0·5%, and this means a considerable reduction in the distance.

In Fig. 3, does V_s remain sufficiently constant during a test for satisfactory results to be obtained? It appears that the formulae in the caption could be written more simply as

$$V_R = V_Y = V_B = \sqrt{\frac{V_{Rm}^2 + V_{Bm}^2 + V_{Ym}^2 - 3V_s^2}{3}}$$

and the method obviously relies on the assumption of balanced voltages in the 3-phase system.

Mr. J. H. Gosden: I would like to draw attention to the risk of cable corrosion by galvanic action due to the use of relatively noble materials for earth electrodes and connections. The effects may be studied by measuring the potential between the buried metalwork and the soil.*

If electrodes buried in coke are placed close to cable routes, failures due to corrosion may occur in 10 years or even less. If the electrodes are located at least 20 ft from the cables, in accordance with the relevant specification, the risk of corrosion damage during the normal life of plant is slight. However, in view of the author's assessment of the value of coke as a back-fill for earth electrodes it seems that the practice could well be discontinued.

The cell between copper and lead has also given rise to corrosion faults, although incidents have been rare in relation to the number of cases in which lead and copper have been buried in close proximity. The risk could be eliminated by using steel in preference to copper and providing a baser metal to give cathodic protection to the steel, e.g. by galvanizing the steel. Magnesium billets cast round steel earthing rods have also been used.† However, in general, experience does not indicate that a drastic departure from existing practice is necessary although, as far as possible, close proximity between bare copper earthing strips or rods and lead-sheathed cables should be avoided.

I would like to ask whether the author has carried out direct-current tests where reinforcing in concrete has been used as an earth electrode. I have found that steel in concrete behaves as a relatively noble material, although when it is connected to other metals polarization limits the current to a low value.

Mr. W. S. Lovely: In my opinion earth electrodes as described in this paper are, in these days, very little needed for the purpose of collection of fault current. There are two zones of fault current: (*a*) that within a circumscribed area, such as a power station with its associated switching station, or an industrial works, and (*b*) the 'system' area outside these limits, more particularly where the distribution from the station is by overhead lines. Where underground cables are used they can be included in zone (*a*).

In fault zone (*a*) each block of equipment should be, and usually is, encircled and interlaced with a substantial copper 'earth' system, and these blocks should then be connected either by further substantial copper connectors and/or by the lead sheaths and armouring, if any, of all the cables between them, in parallel. System neutral should also be connected to this system. Thus, all apparatus is tied down to a common potential—that of earth—and a direct low-resistance path is provided back to system neutral for fault current. This is the condition which should be aimed at, and for it no earth electrodes as such are required. It must be remembered that fault current may enter and leave cable sheaths which lie on any uncontrolled route for such current back to neutral. Control in this sense means insulation or solid bonding. It is also good practice to eliminate differences in potential between apparatus, building steelwork and ground by carrying the copper earth system on building steelwork where possible and bolting it thereto.

The foregoing can be extended to cable systems, since fault current comes from the copper to the outer sheath and the latter invariably presents the path of minimum impedance back to the system, so that fault current tends to return in this way. This was proved many years ago, when tests indicated that at least 90% of the fault current from a cable returns by way of its sheath. If, as should be done, cables are bonded together at the ends of

* GOSDEN, J. H.: 'The Protection of Cable Sheathing against Corrosion', *Chemistry and Industry*, 1956, No, 40. p. 1069.

† COLEMAN, W. E., and FROSTICK, H. G.: 'Electrical Grounding and Cathodic Protection at the Fairless Works', *Transactions of the American I.E.E.*, 1955, 74, Part 2, p. 19.

routes and/or at their points of connection to pieces of apparatus, not only one cable on which there is a fault will carry the fault current but also all the others in parallel.

With zone (*b*) conditions, i.e. where the outer system is on overhead lines, fault current should still return to the station mainly by the tower earth-wire, and it is only necessary to connect all such wires solidly to the station earthing copper system. There is perhaps a case here for establishing earth electrodes at the station to cater for a broken earth wire, in which case fault current would return through the earth. In this instance, the station structure could be used, as has been described by the author, though in all but rocky and similarly bad earthing ground, it should be sufficient to sink copper rods.

Mr. W. H. Thompson: I agree that an earth network should be as extensive as possible. The main purposes for earthing are prevention of danger to life and damage to insulation, and two types of fault can cause these, namely power-frequency faults and lightning.

Lightning is a large electrical charge suddenly injected into the system. If flashover or diverter operation results this charge will be delivered to the earth network, and the potential acquired thereby will vary directly as the charge and inversely as the area of the earth network. The rate at which the charge escapes to earth varies directly as the earth resistance. There may be danger while the charge is above a given value, since it is voltage difference, and not voltage, that is dangerous. Therefore, gradients within the station are important.

Every electrical conductor has a voltage-distribution characteristic unique to its shape and dimensions and the medium in which it is immersed. A simple earth rod has a family of curves, one for each resistivity value of earth in which it is placed (see Fig. A). These characteristics are unalterable whether the 100% voltage is 1 volt or 1 000 volts. Therefore, the 100% value must be kept as low as possible, which is done by increasing the number of rods or extending the area of earth network.

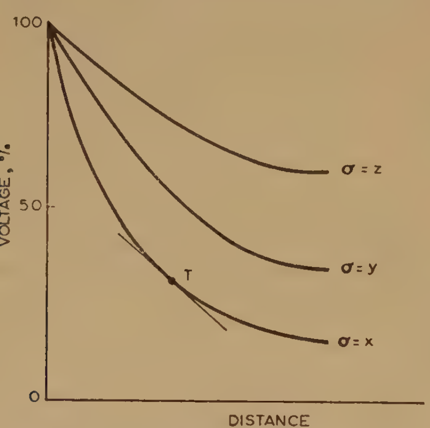

Fig. A.—Voltage distribution from rod through earth of various resistivity (σ) values.
Rod voltage = 100%.

To determine the voltage distribution for a complete earth network a field-form analyser can be used. This was done by a firm of manufacturing electrical engineers in North-West England for a hydro-electric power station in Spain which is built on solid rock. A scale model was made in wood and faced with metal foil to represent the earth metal of the components. These were bonded together in the manner intended in the station proper. The model was then put in the field-form analyser of the electrolytic-tank type and voltage was applied to the metal parts. There was immediately established in the tank a field form exactly similar to that which would occur on site. With the aid of a probe a series of equipotential lines about the station was determined, and these were delineated on a map somewhat similar to Fig. 6. From the closeness of these lines the gradient can be obtained and changes made to the earth network as required.

Mr. L. Csuros: In connection with the author's suggestion that a maximum figure of 430 volts potential rise should be regarded as the criterion of design efficiency, we have to consider that on the British Grid there are a number of stations, perhaps 25%, where this limit is exceeded. In the past, protection was always provided for the Post Office circuits at every substation and power station connected directly to the Grid, and the potential rise of the earthing system was of no interest in this respect. The agreement with the Post Office engineers to dispose of any protection if the potential rise does not exceed 430 volts is fairly recent.

It is not normally possible to avoid overlapping of the effective resistance areas of the nominal electrodes, fortuitous electrodes and interconnections. In general, therefore, the resulting resistance of the earth system cannot be obtained by simply paralleling individual resistances. The separation between electrodes is naturally limited by the site area available, and for the designer it is most important to have a clear picture of how far it is worth while to increase the number of electrodes for a given site area. No reference is made to this problem either in the paper or in the References.

Regarding a.c. measuring methods, the main problems are interference from stray voltages in the ground and interference due to inductive coupling between the current circuit and the voltage-measuring circuit. To eliminate the errors caused by stray voltages, the paper gives a method using 3-phase current supply, which is usually not convenient to arrange. The correction for the error caused by stray voltages can be obtained much more simply by using single-phase current supply and reversing the supply connections for the second measurement. The vector diagram for this test is shown on the left-hand side of Fig. B.

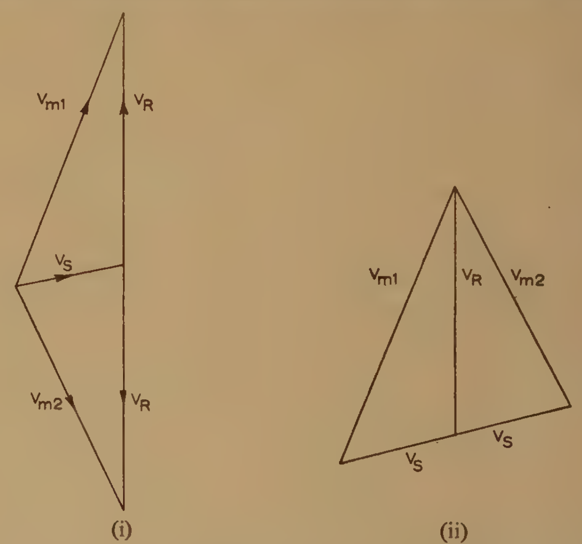

Fig. B.—Vector diagram showing voltage relationships.

V_R = Voltage drop on earthing system.
V_S = Stray voltage.
V_{m1} = Measured voltage.
V_{m2} = Measured voltage with reversed current connections.

On the right-hand side, the diagram is redrawn in such a form that from the magnitudes of the two measured voltages and of the stray voltage, the actual voltage drop on the earthing system can be obtained by simple geometry.

This method and the methods indicated in Figs. 3 and 4 of the paper are based on the assumption that the currents and voltages

are sinusoidal. While it is usually easy to ensure that the current does not contain excessive harmonics, this is not always the case with the stray voltages, and even the reactive component of the voltage drop might contain substantial harmonics since the reactance is proportional to the frequency. Unless, therefore, these methods are used with great caution, and possibly in conjunction with the use of oscillographs, these corrections may introduce additional errors.

Mr. P. W. Cave: The author quotes earth currents of up to 10 kA, but currents of this magnitude usually do not flow in the ground at all. Very largely they return via the sheath and armour of the cable supplying the earth fault, or via the continuous earth wire if it is an overhead line. Their path, from fault to neutral, is entirely a metallic one. The important feature, surely, in the design of any system is the bonding, and if the bonding is adequate and efficiently carried out earthing becomes a matter of secondary importance. Would not an earth-electrode resistance of 10 ohms be quite safe in a station where distribution was entirely by metal-sheathed cables?

I have been associated with a fair amount of earth-electrode measurement and this has been carried out with a very modest amount of equipment. After what can only be described as a large-scale field operation involving a considerable amount of equipment, the author has produced a diagram of equipotentials. Is he satisfied, having looked at the diagram, that the earth-electrode system at this particular generating system is satisfactory, or does he think it could be improved in some way?

Regarding the use of aluminium rods for an auxiliary electrode, would aluminium be a satisfactory metal for this purpose? I should have thought that the oxide film would render it almost useless. Furthermore, is it really necessary to go to all this trouble to determine the resistance of an earth-electrode system of the magnitude considered in the paper? It is usually possible to split such a system into three components and measure their resistances in pairs. From these results, the resistance of each component can be readily determined. This is a very simple method and is free from the type of error mentioned in the paper.

Mr. W. T. J. Atkins: Earthing resistance, or dissipation resistance as it is called in the paper, is an idealized conception which does not, in fact, correspond with any condition met in the practical affairs of electricity supply. It has grown out of attempts to apply the ideas of linear circuits to currents of varying density spread throughout large volumes. In strictness there is no single value of dissipation resistance, because in every case the voltage resulting from an exposure depends upon the routes of the interfering current and of the pick-up circuit jointly, and there is no common residuum to the measurements. It is equally unscientific to appeal to a 430-volt limit of dubious validity.

The resistivity of average soils is of the order of 10^9 times that of metals, and it is no wonder that currents tend to crowd into the latter, in spite of the slightly opposing influence of reactance. On the whole this natural tendency makes for safety, and I feel, with others, that it should be reinforced by the adoption, as a normal practice, of bonding between all metal objects in and near electricity supply stations. At the same time it is to be remarked that large earth-fault currents have been with us for many years, and there is no need to panic about them now.

Mr. F. Tonge: In 1954 I visited Italy to make a survey of distribution systems, including earthing. I shall refer to two 132 kV substations.

The first case is a 20 MVA transformer station. There is a line of earth rods on three sides, and on the west side another line buried deeper and originally intended, with its interconnecting cable, as a separate neutral earth. All earth rods, however, are now interconnected.

Fig. C shows the point of interconnection between west and north sides. It is interesting to note the care which has been taken to ensure an adequate supply of moisture to each earth rod.

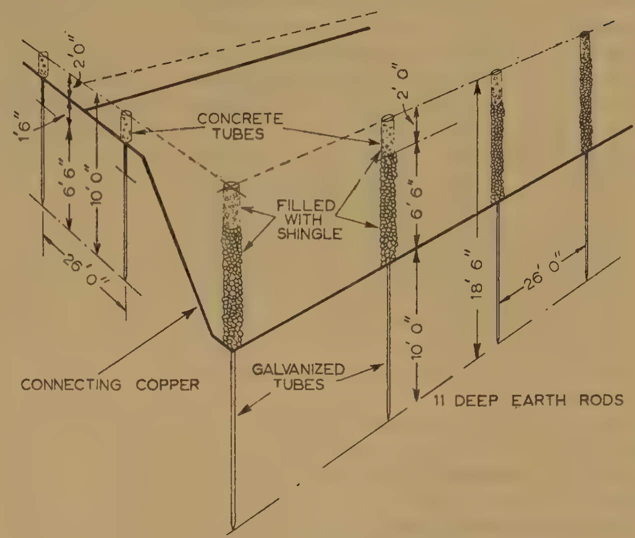

Fig. C.—Sketch showing connections and depth of earth rods.

The dissipation resistance, measured in April, a wet month, was 0·21 ohm. The method used was to inject a current of 100 amp 50 c/s from a distant source. Measurements were taken to establish that step voltages and contact voltages were safe, with a possible fault current of 3 000 amp. At the second substation measurements were taken in June, a dry month; here the soil resistivity was eight times that in the first case.

The station earth consisted of 90 galvanized plates 3 ft 6 in × 1 ft 6 in buried to a depth of 4 ft 6 in, connected by a 2 ft deep network of braided copper, total length 1 400 yd. The dissipation resistance of 1·25 ohms was measured by injecting 25 amp 50 c/s. The fault current was over 2 500 amp. Step voltages and contact voltages were found to be unsatisfactory. Amongst measures taken to remedy this, some earth rods and connections were lowered to a depth of 12 ft; there was an abandoned substation nearby with its own earthing system, and this was parallelled with the new earthing system.

Major E. H. W. Banner (*communicated*): The paper gives a good survey of all forms of earth electrode but does not make specific recommendations for general use. Having been converted long ago to the driven copper-rod earth electrode by Dr. Taylor and his colleagues (see References 1, 2 and 3), in which the economic advantages of this type are shown, I am somewhat surprised to find that this preference is not shown in the paper. For one thing the danger of very high resistance developing at the joint between an earth plate (of copper or cast iron) and its connecting strip is not mentioned, although I was very impressed by this point in Taylor's work. My own experience is mainly in connection with lightning-conductor earths, where sustained currents are not encountered, but it seems to me that driven copper rods form the best general solution, unless there is a local reason against their use, such as very rocky ground where buried strip, sometimes as a mesh, is the only practicable method to use.

Mr. A. R. Parish (*communicated*): The author has shown the difficulty of obtaining an earthing system which will restrict the voltage to earth to 430 volts even in favourable conditions. The example given in Section 11 relates to an earth-fault current which is very low by present-day standards and an estuary site where soil resistivities would naturally be low.

At one site which I know, the most extensive earthing system, using 90 driven rods and over 2 000 yd of interconnecting cable,

has a calculated resistance of about 0·2 ohm. Since rock is near the surface, building structures cannot reasonably be expected to reduce this figure below 0·1 ohm. With an earth-fault current of 27 kA this means a potential of 2·7 kV. By the use of buried conductors to give an equipotential surface in the substation and the insulation of cables and pipes leaving the station, danger may readily be avoided without the prohibitive expense of reducing the resistance to 0·016 ohm, as would be necessary with a restriction to 430 volts.

In this paper the approach seems to be to put in the civil engineering works, measure the resistance obtained, and then add such electrodes as may be necessary to give the required earth resistance value. Such a method is not always practicable, and I would be interested in any information which the author might be able to give on the design of earthing systems before construction begins.

Mr. R. A. Lowe (*communicated*): The author does not mention the galvanic corrosion caused by bonding masses of buried dissimilar metals in earthing systems.

It is well known that the electrochemical potentials prevail under these conditions and that coupling copper to steel and lead produces a half-volt galvanic cell, the copper being the cathode with the steel and lead the anode, the latter liable to corrode. If a large earthing system is bonded to pipework entering a power station area which happens to be coated, rapid damage to the pipework can occur. In a similar manner lead sheaths of cables can be rapidly damaged, as in this case the rate of loss of metal is some 3½ times that with steel for the same current in the circuit. This corrosion caused by galvanic action can be overcome by avoiding the use of copper completely and employing other more suitable metals, or alternatively by putting the entire system of buried metals of the power station under cathodic protection. This latter approach has been carried out on many stations in the United States, where the corrosion problem has been more rapidly appreciated and where cathodic-protection currents required range from 20 to 200 amp per station so protected.

Regarding the measurement of the dissipation resistances, instruments in use for cathodic-protection work will be found, generally speaking, more convenient than those the author is employing, as an identical system is adopted when carrying out a current drainage survey on any buried structure to determine the current required to give cathodic protection. For example, soil-resistivity meters are available which do not require any winding, since they are battery operated and use a special-frequency alternating current from a vibrator. In addition, high-resistivity voltmeters and half-cells are available which can be used for plotting equipotentials quite satisfactorily.

[The author's reply to the above discussion will be found on page 398.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 25TH MARCH, 1957

Mr. E. J. M. Marrian: The author mentions that the paper is based on experience obtained at sites with high soil resistivity. In Table 1 the highest figure mentioned is $0·96 \times 10^5$, and in Table 2, 2×10^5 ohm-cm. In Scotland, however, we are faced with resistivities approaching 5×10^5 ohm-cm, where the problem of providing satisfactory earth connections at power stations and substations is acute. It would be helpful to know of any experience the author may have had with resistivities of this magnitude. Realistic figures may be hard to obtain, since it is well known that high fault currents in rocky soil tend to follow paths different from those followed by lower test currents.

In Section 3.1.8, the author refers to the effect of earth wires installed on overhead lines, but neglects to mention counterpoise earths, which are very often laid in the ground beneath the overhead lines for a few spans out of the station. It is probable that earth wires and counterpoises have some effect on the earth current distribution and, therefore, on the fault potentials in the neighbourhood of the station.

In Section 3.3, the author states that it is generally desirable to provide interconnections between the earthing systems of stations in close proximity. I agree with this, but it is necessary to consider carefully the route of this interconnection in relation to any power or pilot cables in the neighbourhood to avoid damage by induced voltage. I also agree with the statement that it is necessary to limit, as far as possible, any earth fault current carried by the sheaths and armouring of such cables, and one of the ways in which this may be achieved is to provide insulated cable glands at one end.

Fig. 6 gives food for thought in relation to the great effect on earth potentials of the 'fortuitous' earthing point at the pump-house. The effect of the railway lines is also interesting, since, presumably, these are of the normal siding type using wooden sleepers. The author does not mention to what extent the earthing systems of the power station and 132 kV and 66 kV substations are interconnected, and I think a knowledge of this would improve the usefulness of the diagram. The earthing system at the 33 kV and 11 kV switch-house seems to have very little effect on the voltage contours, compared with those of the railway lines and ash ponds. Has the author any explanation of this?

In the case of Generating Station H, it is surprising that a dissipation resistance better than 0·05 ohm is not obtained. I have in mind the case of a similar power station on the coast at which, by attaching earth plates to the outside of a split caisson out at sea and connecting them by copper strips run in separate, normally flooded, culverts for a distance of about 2000 ft to the power-station earth system, a total resistance of 0·01 ohm is expected.

Mr. A. E. Bishop: The reasons for earthing are (*a*) to enable the protective gear to operate, and (*b*) to protect against shock. To produce a satisfactory earth system to enable the protective gear to operate is often not difficult. Protection against shock applies either within and without the station. With all metal work interconnected there is no shock when the whole station is at a higher potential (assuming the surface gradients are not excessive). Where there is the possibility of the transmission of excessive voltage outside the station boundary, protective insulation can be provided. The author has dealt with the insulation of water pipes. An insulating buffer is also feasible for the telephone system. If interconnection with the Post Office telephone system is the only limiting criterion (430-volt rule), an expensive earthing arrangement appears to be easily avoidable.

I should be glad if the author would provide details of the damage referred to in Section 8.

Reference has been made by the author and others to cable sheaths carrying fault current. The fault current will initially be carried by the armouring, and between this and the sheath there is often a moderate insulation. It is then possible for voltages to build up between the armouring and the sheath such that eventually arcing between them will occur, resulting in puncture of the sheath and ultimate breakdown of the cable. This is particularly so when there is poor bonding between the armour and sheath at termination and joint positions.

I notice that the author, for his investigation of the potential distribution round the station, used very short metal probes of the order of 12 in. I should like to ask whether he regards these

as perfectly satisfactory and whether he has carried out tests at greater depths, say 20 ft.

Mr. A. B. Wood: With particular reference to important substations there are two main earthing requirements, namely a sufficiently low impedance at power frequency, and a sufficiently low surge impedance. The interconnection of all structure footings within the area will approximate to an efficient earth mesh, and by tying this to the station earth electrodes, whether they be plates or rods, and to the transmission-line terminal towers plus counterpoise where provided, a sufficiently low value for the ultimate earth resistance is not too difficult to obtain. This resistance could be approximately calculated by simplifying the interconnections to a symmetrical mesh and adding the calculated effects of the various structure footings, driven rods, etc.

As far as lightning is concerned, a switching station of about 700 ft^2 in a bad lightning area would be expected to suffer between one and two direct strokes per year. Consequently some direct-stroke protection will usually be provided, either in the form of overhead earth wires or separate masts. In the former case it is rather more important to ensure that the structure supporting the earth wires is suitably earthed to avoid back flashovers, but in either case connection of the structure or mast to the main mesh formed by the interconnection ought to be sufficient to prevent trouble, since this mesh will provide a fairly low surge impedance, approximating to a radial counterpoise.

[The author's reply to the above discussion will be found overleaf.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 2ND APRIL, 1957

Mr. H. Heimer: With reference to the electrode details, earth plates should be vertically placed, as this gives the better dissipation resistance than the horizontal arrangement; and small-diameter rods where used as electrodes should be increased in number rather than in length to give better results.

The paper deals with the basic principles of design rather sketchily and two fundamental points should be mentioned. (*a*) The calculation of maximum earth-fault currents involves the question of neutral earthing resistors or arc suppressors. The C.E.A. recommendation SA/3 recommends that these impedances should be ignored when calculating fault currents. Does the author agree? (*b*) There is extensive literature on the question of current-carrying capacity of electrodes. Which of the large number of possible formulae does the author recommend?

Much research has been carried out on the subject of corrosion, and in particular the C.E.A. research memorandum R62 shows that great care must be exercised in the design of earthing systems. The effect of electrolytic action may be particularly pronounced where copper is surrounded by coke to provide a more efficient electrode. The result of the electrolysis is to corrode the anode, i.e. the steel and lead. This is not usually serious owing to the large lead and steel areas, and hence low current concentration, met with in practice. However, where the electrode is placed within 20 ft of the cables it may be serious, and for this reason the cables should have those points imperviously sheathed.

It may well be that electrolysis should also be considered in connection with the mesh type of electrodes advocated in the paper, necessitating the taping of the earth strips at the points where they are in proximity to cables.

Mr. J. W. Steeley: In the power station with which I am concerned the earthing system is, according to the paper, like 'Topsy', and in this I think I could even include the 1948 extension. It consists of three or four traditional earth plates obscurely interconnected, whilst their actual physical location has to be carefully recalled to mind before personal site inspection is possible.

I am astonished at the seemingly vast change in approach to this problem which is suggested by the author if an efficient system is to be installed on a new site, and in view of the many difficulties mentioned in the paper, I venture to ask whether any tests are made on new C.E.A. sites, and, where high soil resistivity is found, whether this has any bearing on the final choice of station location? In short, how far does the C.E.A. carry out the recommendations contained in this paper?

The author in his Introduction mentions the increasing use of direct earthing, but he is no doubt aware of the many installations where earthing resistors are in circuit. In my own station, there are three such units in service, two water pots and one grid resistor; on more than one occasion the electrode insulator on the water resistor has shattered under severe fault conditions. Would the author comment on the merits of these types of equipment, and, where water resistors are in service, can he recommend a suitable protective paint for the inside surface of the tank which at the same time preserves good dissipation properties?

Mention is made in Section 3.2.3 of the possibility of the soil drying out after construction is completed. I would be interested to learn what methods are suggested to ensure adequate wetting of the soil to the required depth to avoid this, especially where earth plates are in use.

I would suggest that, in view of the extreme care needed to make all these recommendations effective, some form of regular testing would be necessary. In what form and how frequently should these tests be carried out?

Mr. W. Stankiewicz: The author quotes high values of earth-fault currents. This may be true for transmission networks but for generating stations the tendency is to limit earth-fault currents to 300 amp for the alternator itself by using liquid earthing resistors. For 3 300 volts and less, earth-fault currents in excess of 3 kA will flow only if 'ideal' fault conditions (zero fault impedance) are assumed.

The author stresses the necessity of obtaining low dissipation resistance of earth electrodes. Again, while this may be true for transmission networks, where low values are necessary to ensure adequate values of earth-fault current to operate protective gear, this does not apply to generating stations, where the earth-electrode system is continuous and all neutral points are solidly bonded to it, the earth electrodes only maintaining this system at earth potential. I do not understand why the reactance of the electrode system is considerable at power-frequency currents, but it can be high at high-frequency currents.

I should like to know how the low values of dissipation resistance quoted in Table 1 were obtained, and whether these values tend to change with the seasons. Did the maximum values of fault current quoted for generating stations C and H apply inside the stations or on the grid sites?

In Fig. 7 no earth electrodes for the chimney are shown, and the 132 kV switch-house is solidly connected to the generating-station earth-electrode system. Does the author think that chimney electrodes should be separated from the station system, and, if so, should not the same apply to the 132 kV switch-house, since separation of these three systems will prevent abnormal potential gradients on the station system which may be caused by lightning or external faults.

What are the author's views on provision or non-provision of test links and on methods of jointing of mesh-electrode systems?

Mr. F. Mather: The product of earth-fault current and dissipation resistance in Table 2 gives relatively high voltages. In view of the fact that on systems with continuous earth wires almost every earth fault has a metallic return to the multiple-earthed neutrals, can the author say whether such voltages actually appear at the substation?

Reference has been made to the corrosion of nearby cables by coke surrounding an electrode, but another serious factor is corrosion and consequent reduction in life of the electrode.

Recommendations have recently been made regarding the brazing together of the sections of deeply driven earth rods. Can the author say whether this is necessary?

Improved servings on underground cables not only reduce the effectiveness of the lead sheaths as earth electrodes but also will presumably cause a concentration of anodic corrosion at any point where the serving may be damaged, if there are also copper earthing connections in the adjacent ground.

Station D in Table 1 appears to have the extremely low soil resistivity of 300 ohms/cm^3, and it would be of interest to know whether this is due to any special circumstances.

Mr. H. Cahm: My points are mainly concerned with some of the detailed parts of the earth-electrode systems on medium-size power stations up to 240 MW.

One example of a specific earth electrode is the station chimney earthing system. In most cases there are two chimneys widely spaced which will comprise entirely separate systems each self-contained, mainly for safety purposes. Considering only the portion of the system buried in the earth, the area surrounding the electrode may become thoroughly dried out owing to the dissipation of a lightning stroke and may thus endanger the efficiency of the system by increasing the resistance if this were connected to the main system. For reasons of economy it is not usual to interconnect the two systems.

Another type of electrode not mentioned in the paper is one which has been used on Admiralty land installations. This comprises a spiral copper strap 2 in × $\frac{1}{4}$ in and approximately 8–10 ft diameter overall with 3 or 4 turns wound on edge and laid on a 9 in bed of ash at a depth of approximately 3 ft, with another 9 in layer of ash covering it before back-filling. Two copper strip connections are taken from the outer periphery of the coil to the main earth bar. It is claimed that this electrode gives low values of dissipation.

At one station two strip electrodes, each 300 ft long of 1 in × $\frac{3}{16}$ in copper were laid in puddle clay at the time when the large circulating water-pipe culverts were being excavated, and this provided a very efficient earth without any additional cost of excavation.

Two types of mesh electrodes have been used for chimney earth systems. One represents in plan a tree with trunk connections laid in the ground at a depth of 12–18 in, with a considerable number of branches running out to approximately 80 ft from the base of the chimney. Another system represents a portion of a spider's web, and these electrodes have proved quite effective and not too expensive.

It has been specified on occasion that the main station earth bar should be connected to the principal stanchions of the superstructure by means of large-diameter brass bolts screwed into the main members and fastened with contact nuts. This has helped considerably to lower the resistance of the earth network.

Whilst it is appreciated that the low total values of resistance shown in Table 1 are desirable, these appear to be extremely low when compared with values obtained at a number of power stations in the North West.

Mr. H. Diggle: An example where the electrolytic-bath techniques has been used to study voltage distribution under fault conditions is recorded in Fig. 9 of a paper* which Mr. E. R. Hartill and I presented before The Institution in 1954. The study related to a hydro-electric station to be built on solid rock, which in common with the water was of high resistivity. Equipotential lines were plotted to determine where there might be undesirably high voltage gradients in and around the station which could be dangerous to the operating personnel.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. J. D. Humphries (*in reply*): Numerous references have been made to the figure of 430 volts quoted as a criterion of earth system efficiency. It must be pointed out that this figure was used in a very arbitrary manner with no great faith in its validity. It did seem, however, to offer a satisfactory starting-point for design work, but if a sound technical argument could be put forward for an alternative I am sure that all engineers concerned with this work would be grateful.

Reference has also been made to the magnitudes of earth-fault currents quoted in the paper and apologies are due for the lack of clarity on this point. The currents quoted are the calculated maxima flowing through the actual electrode systems, and do not include components flowing within the station. Earth wires and cable sheaths are considered to form part of the station earthing system.

In reply to Mr. Gosland, I have generally considered 3 sec to be the maximum duration of fault current likely to occur when magnitudes near the maximum calculated are being considered.

Both Dr. Tagg and Mr. Csuros refer to the 3-phase a.c. method of measurement, and in this connection I would confirm that the balance of the normal 3-phase system is sufficiently good to avoid any appreciable errors. It has also been found in practice that the stray voltage generally remains sufficiently constant in magnitude and phase to permit of fairly accurate measurements. In most large stations the test current is obtained from an existing 3-phase supply with its neutral solidly bonded to earth, and it is inconvenient to reverse the polarity of one phase. It was for this reason that the 3-phase method was suggested instead of the method mentioned by Mr. Csuros. Oscillograph checks made during test have shown that the percentage of harmonics occurring do not generally seriously impair the accuracy of measurement.

In reply to Mr. Gosden I would confirm his finding with regard to the electrochemical behaviour of steel in concrete. Tests carried out at substations where reinforced concrete piles have been used as earth electrodes showed that the reinforcing steel was behaving in a manner closely allied to that of the station copper earth busbar.

Mr. Lovely stated that the majority of the fault current due to an earth fault on a cable would return along the cable sheath. The reduced impedance of this path would certainly lead to this expectation, but in practice it would not always appear to be so, and tests which I have carried out have given occasions when only 30% of the total current has returned along the cable sheath.

I assure Mr. Cave that the work expended on producing the potential distribution surveys has been well worth while. In several cases faulty equipment and unsatisfactory layouts have been discovered, but by far their greatest benefit has been the

* DIGGLE, H., and HARTILL, E. R.: 'Some Applications of the Electrolytic Tank to Engineering Design Problems', *Proceedings I.E.E.*, Paper No. 1627 M, February, 1954 (101, Part II, p. 349).

assistance given to future designs by an appreciation of the efficiency of existing ones. The use of reinforced concrete as electrodes was developed after interpretation of potential distribution plots.

I agree with Mr. Atkins that no satisfactory conception of earth-return circuits exists at present, but until such a complete theory is achieved it seems necessary to develop our present empirical methods as best we can. I disagree with him on his attitude to large earth-fault currents, which, after all, are increasing progressively every year, bringing us sooner or later to the point where a reorientation of our viewpoint becomes desirable.

I agree with Mr. Parish that the insulation of cables, pipes, etc., may be the only satisfactory answer on occasions to the problem of large voltage rises on earthing systems.

The design of earthing systems is very much an art, and experience and previously published information are the only things which can assist a designer in judging how much to rely on individual components of a given system and when to plan for additions.

In reply to Mr. Lowe I would mention that the instruments designed for work on cathodic protection are normally concerned only with d.c. electrolytic measurements, whereas in the measurement of dissipation resistance it is a.c. values which are of importance, the electrolytic potentials having to be excluded.

I have had little experience with the extremely high soil resistivity conditions quoted by Mr. Marrian, but I would agree that design and measurement become extremely difficult under these conditions.

Mr. Marrian makes several queries about Fig. 6 and I will answer these as best I can. Tests at other stations as well as this particular one have indicated the effect on potential distribution caused by railway lines, even main lines which are not connected to the station. The power station and all the various switch-houses and substations had their earth systems interconnected. The 11 kV and 33 kV switch-houses do have considerable effect on the potential distribution, but this tends to be masked by the particular contours chosen for the final published drawing.

In reply to Mr. Heimer, it is generally desirable to ignore the effect of limiting impedances in neutral connections when calculating fault currents. This is particularly important in the case of liquid resistors, which are liable to internal flashovers. The work carried out by the E.R.A. seems to be the most convenient on the subject of current capacity of earth electrodes.

I would remind Mr. Steeley that all recommendations contained in the paper represent my personal opinions, which are not necessarily those of the C.E.A. Liquid resistors have the great merit of a low impedance to steep-fronted waves, as compared with grid resistors.

The difficulty of carrying out routine tests makes it very necessary to ensure the reliability of the original design in order to avoid the necessity of such tests.

Mr. Stankiewicz's query concerning the figures in Table 1 is answered as follows: Station E was measured with the a.c. potentiometer; the others were measured using the 3-phase injection method. Variations with the season are not known. The maximum values of fault current quoted generally applied to the grid site.

My personal opinion is that test links are not of very great value in the large installations under consideration, where isolation of sections is very difficult.

In reply to Mr. Mather's query, the only direct indication of high voltages occurring on equipment has been the flashover of telephone and other similar types of gear, although the Post Office are now carrying out measurements with fault-recording oscillographs in an attempt to settle this question.

Several rods which were driven for test purposes to a depth of 35 ft were recovered by using ratchet jacks and found to have partially unscrewed at some of the joints. This would appear to confirm the desirability of locking these joints in some manner.

Station D was built on an old rubbish dump, which possibly explains the very low soil resistivity.

DISCUSSION ON 'ELECTRICAL ENERGY FROM THE WIND'*

BEFORE THE SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP AT BIRMINGHAM, 14TH JANUARY, 1957

Mr. J. R. Anderson: I am interested in the reference to solar radiation for space heating, costing 2d. per kilowatt-hour. I notice there is also mention of air-conditioning; surely if solar radiation is available there is no need to go to all sorts of elaborate contraptions to get space heating?

Mr. H. B. Mellor: The author mentions that around the 17th–18th century approximately 10 000 windmills were working in England, each developing between 30 and 40 h.p. A figure of 400 000 potential h.p. is not to be neglected and, I consider, warrants an investigation on the lines of the present research.

Some of the costs quoted by the author are not relevant. If a certain service is wanted the cost of that service does not always enter into it. If a unit of electricity costs 1s., and only a few milliamperes per year will be used, that 1s. is well spent. There is no yardstick to measure one cost against another, in particular the cost of a unit of energy for operating a telephone by a solar battery, or, at the other extreme, bullocks used for pumping water.

Regarding power from waste vegetable matter, some years ago a firm in the North of England ran all their generators by a gas engine off producer gas made from wood shavings, sawdust and horse manure. The plant maintenance was heavy, but these things are worth while if no other power source is available.

The author describes the storage of energy by chemical means, such as producing hydrogen. Before the war the Germans carried out quite a lot of work on hydrogen production as an energy source for motive power, electrical energy, when available, being fed into high-pressure electrolizers and energy being taken off when required as hydrogen and used in Horren hydrogen engines, etc.

Mr. H. F. Jones: I would be interested to know how far the

* GOLDING, E. W.: Paper No. 1727 S, November, 1954 (see 102 A, p. 677).

normal wind flow is disturbed by the erection of a windmill of the type described, and how many such devices could technically be erected on one site.

Is there any indication that the weather has been affected noticeably by the erection of large windmills?

Mr. J. S. Woodhouse: The problem of using wind power to supply man's needs on land is perhaps one of the most fascinating, and its proper solution would have tremendous effects, both political and economical, upon the most underdeveloped areas of the world.

However, I cannot help but feel that optimism rather outstrips the real problem of this particular application, and that the supply of electrical energy can only be by means of electrical transmission. Even if a successful wind generator were designed and installed, owing to the vagaries of the wind and the highly developed skill undoubtedly required to maintain this apparatus, I feel that it would rapidly fall into disuse, so that the hope of supplying electrical energy to the people in the remote and windy parts of the world, by the use of wind energy, still only exists as a hope. Does the author share these sentiments?

Mr. D. P. Sayers: We are told that there were 10 000 windmills doing good work in the old days, and when their working days were over they became venerated as ancient monuments. I would like to think that our Grid pylons will be similarly revered when their working days are over. The fact seems to be that the modern windmill, designed by modern engineers, just does not work. I had the advantage of seeing the 100 kW Andreau model in course of erection at St. Albans; all the aerodynamic side was designed by de Havilland, according to the very best aircraft practice, and a fortune was spent on it. In the end it never worked, and it has now been packed off to Algiers. We are told that the 100 kW machine in the Orkneys is still standing, but would the author say whether it is working on the scale for which it was designed?

The difficulty is to design and build a machine large enough to produce useful power at normal wind speeds, i.e. 15–50 m.p.h., which will stand up to gusts of 90–100 m.p.h. The author points out that the power varies as the cube of the speed, consequently the stresses at these high gusts are enormous. My feeling is that the problem has not yet been solved.

Commenting on the author's estimated transmission cost of 10–11d. per kilowatt-hour for transmitting 1 000 kW for 300 miles, I can only say that these figures are about one hundred times the normal commercial transmission costs on the British Grid system.

Dr. W. G. Thompson: Electrical engineers, particularly those engaged in supply and distribution, as well as manufacturers, must take a share in having caused the disappearance of windmills from landscapes of this country and many Continental countries. Wind power used directly at the mill has formed an integral part of the economies of civilized countries for many centuries, and its abandonment has been mainly a matter of economics.

I am not surprised that aircraft designers have not been particularly successful at their first efforts to design a modern counterpart of the old windmill, because we have experienced exactly the same problem in trying to interpret data from desk and ceiling fans in terms of aerofoils and air screws. The difference lies in the values of Reynolds numbers and aerodynamic phenomena at comparatively low speeds, and to which data associated with even moderate aircraft speeds are no longer applicable.

I do not think that we have arrived at the stage when an economic success can be made of modern windmills, and it is obvious that more research is required.

Mr. E. W. Golding (*in reply*): As Mr. Anderson remarks, when there is sufficient solar radiation, in the daytime, nothing more is needed for space heating, but in some tropical areas, particularly in the arid zones, space heating is needed at night, so that the problem is to devise a method of storing the heat for a few hours.

I am glad that Mr. Mellor appreciates the potentialities of wind power in this country. His figure of 400 000 h.p. is a significant one, but, in fact, it would be possible to install a much greater capacity of wind-driven plant if it were necessary to do so. I agree that it is difficult to say when a service is uneconomic in a remote area, because there is often no alternative cheap method of producing power with which local generation can be compared. The information which Mr. Mellor gives on the use of waste vegetable matter and on hydrogen storage is interesting, and there is little doubt that there are possibilities in these two methods for firming the random power supplies from the wind or the sun.

The answer to Mr. Jones's question, about how many windmills can be erected on one site, is that the machines should be arranged so that the distance between them is of the order of eight times the diameter of the windmill rotor. There has never been any indication that large windmills have any effect on the local climate. Mr. Woodhouse rightly emphasizes the tremendous effect which wind power could have in underdeveloped areas, but I feel that he is unduly pessimistic about the success of wind-driven machines in these areas. Many, of small capacity, have already been used successfully without calling for the highly developed skill which he suggests would be needed to maintain them.

I cannot agree with Mr. Sayers that modern windmills do not work. Throughout the last war, and since, wind-driven generators of capacity up to 70 kW have been used successfully in Denmark, where, following the successful development of a 45 kW machine of a new type within the last few years, a 200 kW machine is now being put into service. It is unfortunate that many people, including Mr. Sayers, have regarded the two 100 kW wind-driven machines which formed part of the research effort on wind power in this country as prototypes upon the success or failure of which the possibilities of wind power should be judged. In fact, they were built before any experimental work on windmill design had been done, as pilot plants from which some experience on operating machines connected to a network could be obtained. In view of the lack of information on such plant when they were built, it could not be expected that they would be certainly successful or that they could serve as prototypes. They have, in fact, served a very useful purpose in throwing light on the problems to be met with in a project of this kind. It is doing less than justice to the manufacturers of the machine, which was installed temporarily at St. Albans, to say that it never worked; there was no opportunity to test it satisfactorily before it was shipped to Algiers where, I understand, the electricity supply authorities are now installing it with the intention of putting it through a full schedule of tests. It is true, as Mr. Sayers suggests, that the stresses experienced at wind speeds of 100 m.p.h. are very high, but the Orkney machine most certainly stood up satisfactorily to wind speeds well over 100 m.p.h. and, so far as I know, none of the large experimental machines built during the last few years has failed owing to inability to withstand the effects of high wind speeds. One can easily understand that transmission costs on the British Grid are very much smaller than those of transmitting loads of the order of 1 000 kW over distances of 300 miles, but the figure of 10d. or more per kilowatt-hour for transmission costs in this case are based upon careful estimates of the costs of transmission lines and cannot well be disputed. I was glad to have Dr. Thompson's confirmation that experience in the design of aircraft is not necessarily a guarantee of success in the design of a windmill. The problems to be met in the two cases are very different and we are still working to obtain basic data for windmill design.

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A DEEP ELECTROLYTIC TANK FOR THE SOLUTION OF 2- AND 3-DIMENSIONAL FIELD PROBLEMS IN ENGINEERING

By E. R. HARTILL, B.Sc.(Eng.), Associate Member, J. G. McQUEEN, and P. N. ROBSON, B.A.

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SUMMARY

The electrolytic tank is playing an increasing part in electrical-engineering design departments, particularly for the analogous solution of 2-dimensional field problems. The paper describes the design, construction and operation of a general-purpose deep tank for solving both 2- and 3-dimensional problems. Details are also given of the precision electronic potential and gradient measuring equipment, together with an assessment of the accuracy achieved and the precautions required.

The use of the tank is illustrated by a few typical applications which have been studied by the computation group within a large electrical-engineering organization.

(1) INTRODUCTION

The use of the electrolytic tank for the analogous solution of field problems is by now an accepted technique, and has been extensively employed[1–4] on 2-dimensional field problems and on those 3-dimensional problems which have rotational symmetry about an axis and for which a wedge-shaped tank can be used.

The extension of the technique to solve 3-dimensional potential field problems involves the use of a deep electrolytic tank, together with facilities for plotting and recording the potential distribution at any plane of the problem under investigation.

Apart from the 3-dimensional aspect, 2-dimensional problems are also catered for by means of a false bottom to the tank. The tank is made fairly large in both area and depth, in order to accommodate larger models with consequent greater accuracy of representation.

(2) DESIGN OF ELECTROLYTIC TANK

(2.1) Tank

The 3-dimensional electrolytic tank is 6 ft × 4 ft internally and has a 3 ft effective depth of water; these dimensions were considered adequate for all problems which could be envisaged. It was decided to construct a wooden tank on account of the insulating boundaries presented to the water, and since either insulating or conducting boundaries may be required at different times, it is much easier to line an insulating tank wall with conducting strip than to insulate a metal tank.

The construction of the tank is best appreciated by reference to Fig. 1. It is made from $2\frac{1}{2}$ in thick timber with double grooves and loose tongue joints which, when sealed with bitumen, provide an excellent watertight seal which does not tend to open with movement of the tank. The sides and bottom are reinforced with long 1 in-diameter steel tie rods screwed at each end and passing through holes bored in the timber. These tie rods, which are bolted through steel clamping plates, also serve to maintain the requisite pressure on the joints. The inside of the tank was first impregnated with linseed oil and then thoroughly varnished.

The tank is mounted on two steel channels which are in turn supported at four corners by four 4 in-cube rubber pads. With the tank full and holding two tons of water, the compression on the pads is such that the water surface is free from any serious ripples. Adjustable set-screws are provided at each corner to prevent inadvertent tipping of the tank.

The tank can be filled in about 60 min from the high-pressure town water main via a filter, and can be emptied in 10 min by a pump to a drain outside the building. The water is changed regularly every three days.

(2.2) Plotting Table and Carriage

The electrolytic tank follows previous practice[3] in having a plotting table mounted directly above the carriage, which supports the probe and illuminated cross-wire. The position of the probe is thereby indicated on to paper positioned on the transparent plotting table, made from $\frac{3}{8}$ in armour-plate glass suitably drilled and bolted to an angle-iron framework as indicated in Fig. 1. The framework can be swung into a vertical plane, either to gain access to a model beneath or to form a plotting table when plots are being made at depth in a vertical plane. A subsidiary carriage and stays are provided so that the rather heavy plotting table can be locked and remain tilted and stable at any angle to the horizontal.

The probe carriage consists of two grooved wheels running on one round side-rail, with a plain roller on the opposite rail. Owing to the rather large span of over 4 ft, the plain roller is driven by a shaft running through a metal tube and carried by Oilite bushes. This shaft carries the nearside grooved wheels, and terminates in an operating handwheel as shown in Fig. 1.

The head carrying the probe assembly is traversed across the tank by means of a handwheel driving a square-thread screw of suitable pitch.

(2.3) Two-Dimensional Plotting

For conventional 2-dimensional plotting in the surface of the electrolyte the deep tank is provided with a false bottom 1 in or more below the water surface. This comprises a tray made from special water-resistant laminated wooden bars supporting two 3 ft × 4 ft armour-plate glass sheets. These two sheets of glass, which are strong and portable, give effective electrical separation of the 3 ft depth of water beneath, from the 1 in or more above. The 2-dimensional models are then suitably disposed in the upper layer of water.

The tray with its plate-glass base can be levelled by means of adjusting screws suspended from the lugs in the side of the tank. The same adjusting screws also impart the necessary tilt for 2-dimensional models simulating rotational symmetry.

For plotting equipotential lines a needle probe is used. The long thin steel needles commonly used for darning silk material have been found most suitable, because of their resilience and small diameter.

When surface potential-gradient measurements are required the brass chuck holding the steel needle is replaced by that holding the double probe shown in Fig. 2 This probe is basically similar

The authors are with the Metropolitan-Vickers Electrical Co., Ltd.

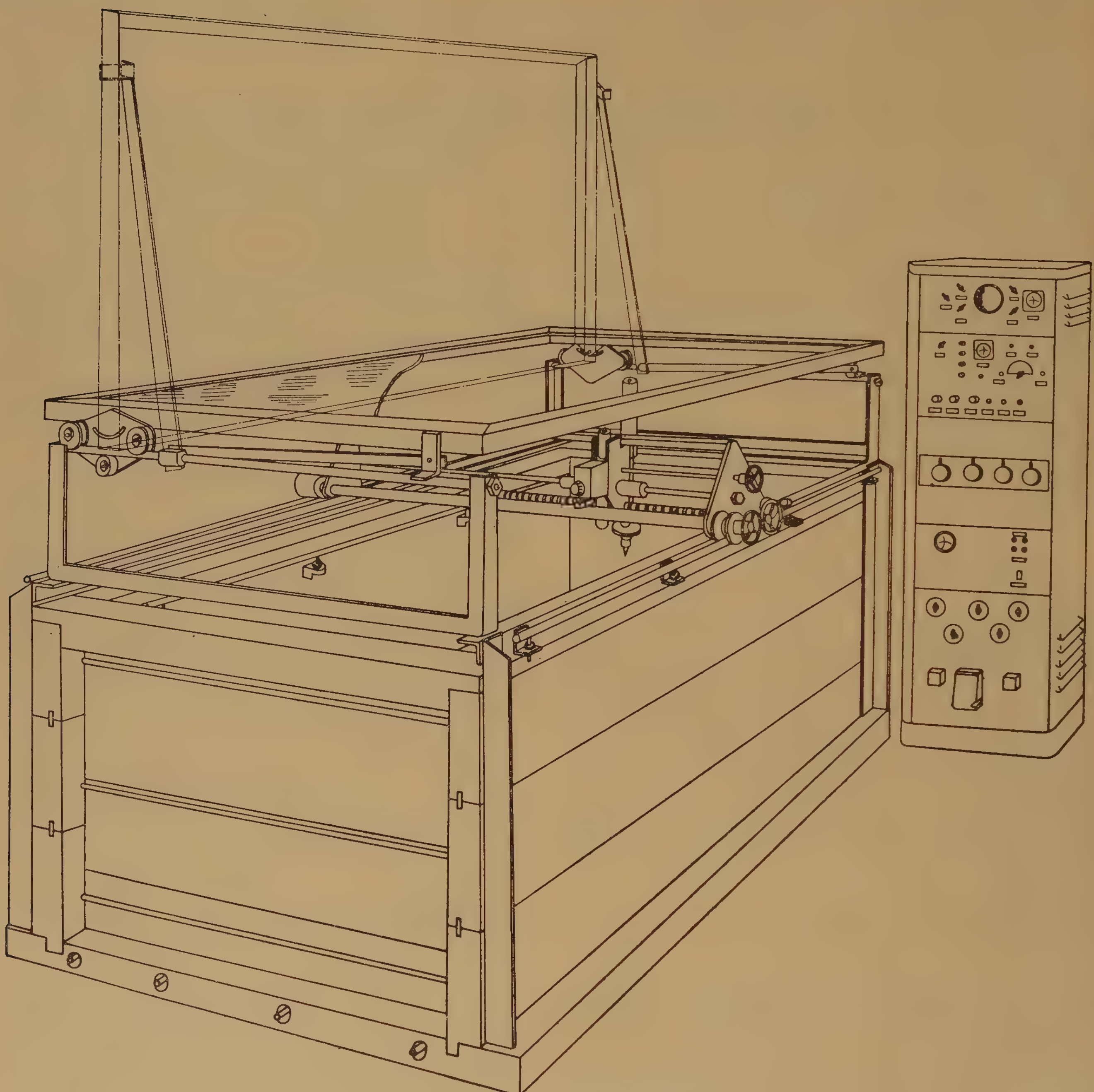

Fig. 1.—General view of deep electrolytic tank.

to those used by Messrs. Sanders and Yates,[5] differing only in design details.

The probe, which was precision turned on a watchmaker's lathe, consists of two Perspex capillary tubes mounted in a length of $\frac{3}{4}$ in-diameter Perspex rod. The capillaries are 4 mm long, of which 2 mm is immersed in the electrolyte during the plotting. The outside diameter is 1 mm, increasing to $\frac{5}{32}$ in for a length of $\frac{5}{8}$ in inside the main body of the probe. These relatively large internal chambers house small spirals of platinum wire to which a connection for potential measurement is made by means of the flexible leads as indicated. The whole internal chamber and capillary tube is filled with water with the aid of an hypodermic syringe.

The Perspex probe is used in preference to the normal metal probe in order to remove the effects of polarization from the surface of the electrolyte during plotting, and to reduce the perturbation effect.[5] Meniscus changes, however, proved to be a serious disadvantage until a silicone varnish was found which could control the degree of upward meniscus at each probe. The bottom of the probe (inset, Fig. 2) is coated with this varnish to within 2 mm of the tip of each capillary tube.

The double probe can be rotated through any angle in a horizontal plane by means of a mechanism and pointer which indicates the movement on a large circular protractor. This facility is required when gradient components are required in two directions mutually at right angles.

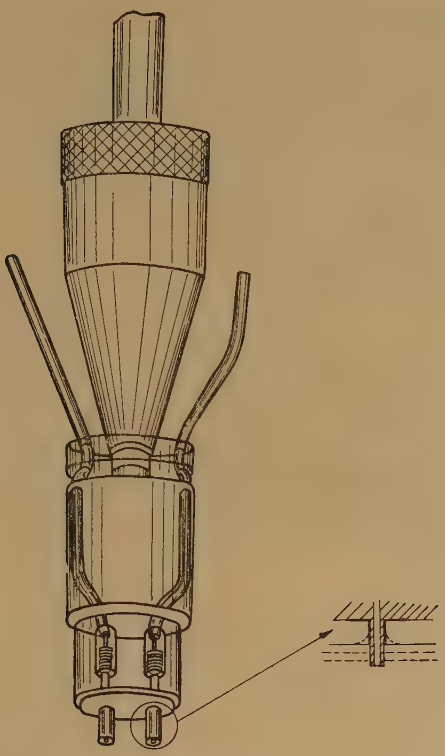

Fig. 2.—Perspex double probe.
Inset: Effect of silicone varnish coating in reducing the meniscus shown dotted.

(2.4) Three-Dimensional Plotting

In addition to the movement of the probe head in a horizontal surface plane, arrangements have been made for a long capillary-tube probe to be moved in a series of either vertical or horizontal planes at various depths. This is effected by means of a third handwheel (Fig. 1) which operates a splined shaft carrying a sliding pinion, which in turn imparts vertical movement in depth to a rack. The rack has a vertical hole which carries the capillary-tube probe, and a second lamp house and cross-wire located directly above the probe indicates its position on the plotting table.

For plotting in depth in any vertical plane along the length of the tank, the plotting table is swung into the vertical position shown dotted in Fig. 1 and rolled across the width of the tank for an appropriate distance. It is then clamped into position immediately behind the vertical probe and the lamphouse using an illuminated cross-wire on the side facing the table.

For plotting in depth in any horizontal plane, the plotting table occupies its normal flat position and a probe of appropriate length is adjusted by means of the rack to operate in the required horizontal plane. A set of four such probes of different lengths covers all depths likely to be required in practice.

Each probe consists of 5 mm o.d. glass capillary tubes through which a single-core braided-copper-screened polythene-insulated cable runs to the 0·5 mm-diameter conducting probe, which terminates in a glass-to-metal seal so that only a 2 mm length is in contact with the electrolyte. Connection is made to the cable core and screen by means of suitable seals at the tip of the tube.

Although provision has been made for plotting in depth as indicated above, not all 3-dimensional problems require this facility. The models for many such problems frequently have a single plane of symmetry which may be made to coincide with the free surface of the water. In such cases, plots in this plane can be made in the surface of the water, using the conventional probe and horizontal plotting table.

The models used for 3-dimensional problems, which are usually rather large and relatively heavy, are carried on two $\frac{3}{4}$ in-diameter steel bars located about 3 in above the water surface. These bars run for the whole length of the tank, and are fixed to the tank sides and made truly parallel by means of adjustable lugs. The models are mounted in a framework which can be removed from the parallel bars and replaced in the same position as required. All metalwork which might occasionally come into contact with the water is heavily nickel plated.

(3) THE MEASUREMENT OF POTENTIALS AND POTENTIAL GRADIENTS

(3.1) Principle of Measurement

The potential between any two points in the electrolytic tank may be measured as a fraction of the potential appearing between two model electrodes A and B (Fig. 3) immersed in the electrolyte. This measurement is made by dividing the 100% potential between the electrodes using an accurate resistance box R_B, and comparing for equality with the potential between the probe

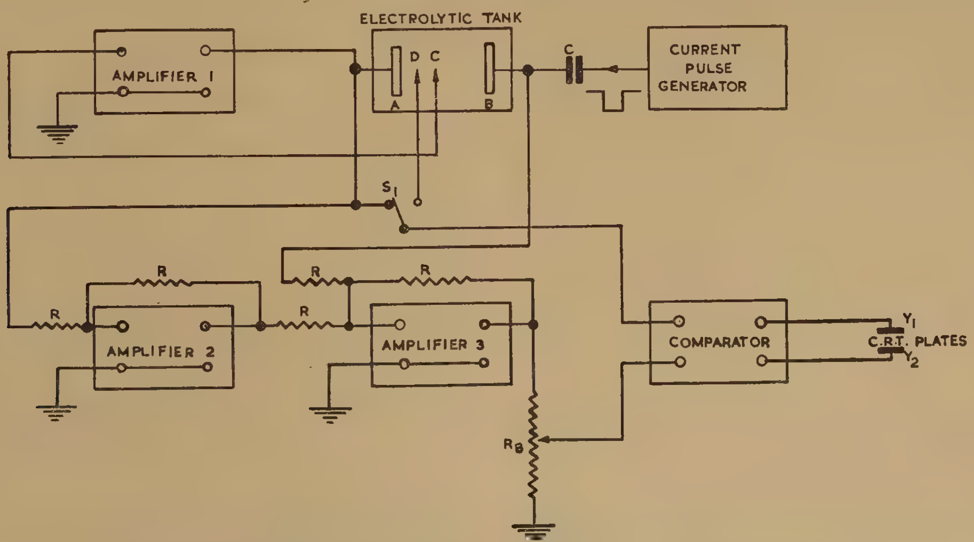

Fig. 3.—Circuit arrangement for measurement of potential and gradient.

C and electrode A, or, for gradient measurements, the potential between the two inputs C and D from the double probe.

It has been shown by Sander and Yates[5] that the use of square-wave excitation provides an effective means of avoiding error due to polarization and stray reactances. The effect of polarization over short time intervals is represented by a capacitor coupling an electrode to the electrolyte and is zero at the instant of a step function. Although time-constants in the system produces a spike which prevent measurement at that instant, the trailing edge of the spike is asymptotic to the polarization slope. Over short time intervals the slope BC [Fig. 4(*d*)] is

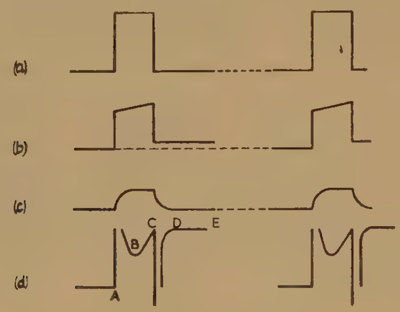

Fig. 4.—Pulse excitation.

(*a*) Square current pulses.
(*b*) Potential between model electrodes in the tank (polarization emphasized).
(*c*) Gradient at probe (integration due to high probe impedance).
(*d*) Amplified difference between a known fraction of signal (*b*) and (*c*).

linear, and when projected back to the instant A of the step function, balance is indicated at that point. The reader is referred to the original paper[5] for further details.

The present deep-tank equipment, however, uses square-pulse excitation of small pulse/space ratio [Fig. 4(*a*)]. The tank current between pulses is extremely small, and the polarization rate between pulses is therefore slow. This feature facilitates equalizing the divided electrode potential with the potential being measured, since it is possible to assess more accurately the condition where the low polarization slope DE [Fig. 4(*d*)] meets point C in the balance condition than to observe where the line BC produced meets A.

(3.2) Use of Feedback Amplifiers*

It is preferable to arrange that both pulse potentials being compared are referred to a fixed (near earth) potential rather than being the difference between two pulse heights, because the comparator input approaches its true value exponentially, owing to the time-constant comprising the high probe impedance and the coupling leads and other stray capacitances. Any error during the exponential rise would therefore be proportional to the pulse amplitude at the probe relative to earth. With the probe at earth potential, however, the time-constant effect is a minimum.

The above improvement is achieved by connecting the probe C to the input of a high-gain d.c. feedback amplifier 1 (Fig. 3), the output of which is fed to electrode A. Provided that the output stage of this amplifier can supply the necessary current and voltage variations, the electrode A will be driven to maintain C at a constant earth potential under all conditions of tank current. Electrode B is fed from a negative-pulse current generator, the large coupling capacitance *C* being necessary to avoid any d.c. component through the tank.

This method dispenses with the 3-winding transformers normally employed[5,7] and enables a single, rather than a double, differential amplifier to be used.

For the measurement of gradient, switch S_1 selects the potential appearing at probe D, while for potential measurements it makes contact with electrode A. A further switch, not shown in Fig. 3 but mounted on the probe head, permits potential measurements to be made relative to probes C or D or to the mean potential of the two. Reversal of the supply to the two electrodes is used to measure negative gradients without rotating the probe through 180°.

The potential appearing between the electrodes A and B is derived in single-ended form by the use of feedback amplifiers 2 and 3, in which the potential at A is inverted and added with further inversion to that of B. The resulting 100% potential difference between A and B is then divided in a precision resistance box R_B, where it can be compared by means of the comparator with the potential between C and A or between C and D. Preset adjustments are provided to set the gains of amplifiers 2 and 3 to exactly unity, using the method of injecting a square pulse and observing a null at the junction of two equal resistors R connected between input and output of the amplifiers and reversible to check their own equality.

(3.3) The Comparator

The comparator input stage consists of two pentodes with a common cathode impedance of about 10^9 ohms derived from the use of another pentode, the screens of the input pair being driven by the common input waveform via a cathode-follower. In this way, differences between the internal amplification factors of the input pair do not give rise to differential errors. The second stage consists of another differential pair, the Y-plates of a cathode-ray tube being connected between the two anodes. Since none of these valves can be driven into grid current, the large spikes in the differential waveform have no ill-effect.

(3.4) Practical Arrangement of Electronic Equipment

The electronic equipment is contained in a rack (Fig. 1) which stands to one side of the electrolytic tank. It is necessary, however, to use short lengths of low-capacitance connectors to both probe inputs, for reasons of adequate frequency response. The first valves of amplifier 1 and the comparator are therefore housed in a small unit mounted on the probe head.

Low-capacitance coaxial leads are used to connect amplifier 1 to electrode A, and the current-pulse generator to electrode B, while separate low-capacitance connectors feed the electrode potentials back to the main rack. In this way, inaccuracies due to the resistance of the electrode leads are avoided.

(3.5) Accuracy of Electronic Equipment

Factors in the measuring system, as distinct from probe, electrode or electrolyte effects, which can affect the accuracy are as follows:

(*a*) The common signal rejection ratio of the comparator: the error due to this is less than 0·01% of the gradient or potential measured.

(*b*) Noise in the amplifiers and comparator: this is of an order lower than the smallest resistance-box step.

(*c*) Deviation from unity gain of amplifiers 2 and 3: very accurate adjustments enable this to be set and frequently checked, as indicated in Section 3.2.

(*d*) Resistance box errors: for potentials and gradients down to 1% of the tank potential the accuracy is better than 0·1% of the measured potential or gradient; for lower measurements the smallest resistance step becomes greater than 0·1% of the measured potential.

(*e*) Error due to limited gain of amplifier 1: the negative pulse potential appearing at probe C is equal to the potential at electrode A divided by the gain of amplifier 1. When C is close to electrode B the potential of electrode A is almost equal to the total tank potential.

* Since the design of this equipment was completed, the work of Dr. Hollway[7] has been brought to the authors' notice; here, feedback amplifiers have been applied to electrolytic-tank measurements using sinusoidal excitation.

The error due to the finite gain of amplifier 1 is therefore, in the worst case, equal to (1/gain) × total tank potential. This error can be taken into account when plotting results, or can be cancelled by feeding the correct proportion of electrode A potential into the comparator. It is preferable, however, to make the gain of amplifier 1 as large as possible consistent with a reasonable bandwidth and a good margin of stability round the feedback loop. In the present case, amplifier 1 has a gain of 20 000 and a bandwidth of approximately 300 c/s. The error due to pulse potential at probe C therefore falls to 0·005% of the potential at electrode A within about 1 millisec after a step function; this is small enough to be neglected.

(4) TECHNIQUE AND OVERALL ACCURACY

(4.1) Electrodes and Electrolyte

One of the problems encountered in the application of the deep tank was the manufacture of large models with electrodes of varying shapes and of large surface area. Initially it was found possible to brass-spray Bakelite boards to form satisfactory plane electrodes, but this technique proved very difficult on curved electrode surfaces since the coating did not adhere very well. Furthermore, owing to its granular nature and low conductivity, it did not give a well-defined surface, particularly at the edge of the electrode where it broke the surface of the water. In addition, plain brass electrodes, whether in sheet or in sprayed form, had a greater surface impedance with tap water, as evidenced by the imprecise balance obtained on the oscillograph. The effect could be reduced to insignificant proportions by coating the brass with colloidal graphite,[6] but it was subsequently found that the graphite or its carrier dissolved in the electrolyte, to produce what was considered to be localized zones of high conductivity.

The most satisfactory electrodes have been made of silver-plated brass, which gives negligible polarization effect with tap water. The models can be fabricated or spun from brass or copper sheet when extensive electrodes are required. For the higher accuracies, of course, machined and silver-plated brass surfaces are essential.

Tap water, which has been used as the electrolyte, has been found quite satisfactory. This is fortunate, since the making up and handling of two tons of acid or alkali electrolyte would have been formidable. Temperature variations were never found greater than 1° C throughout the electrolyte. This is particularly important, since tap water has a temperature coefficient of resistance of approximately 1% per deg C.

(4.2) Overall Accuracy

In order to test the accuracy of the equipment a comparison was made of the measured and calculated values of gradient for two known electrode configurations. The measurements were made in the surface of the electrolyte by means of the double probe which had not been treated with silicone varnish.

Numerous uniform field tests were made with brass-sprayed parallel Bakelite boards 3 ft 6 in wide × 2 ft deep and spaced 10 in apart. Tests for a varying gradient were also made with copper-plated and graphite-coated concentric-cylinder electrodes of 2 in and 12 in radius with a 12 in axial length. For reasons stated in Section 4.1, the accuracy with these electrodes was only of the order of ±3% when measuring a gradient (defined as the percentage voltage across the double probe) of the order of 2% of the 100% voltage applied to the electrodes. Furthermore, in the case of the parallel plates, owing to variations in the Bakelite board, it was difficult to maintain the 10 in spacing to better than ±0·2%. A further loss of accuracy was caused by the continually varying meniscus between the probes.

The theoretical gradient in the concentric electrode system varies inversely as the radius, and agreement within ±0·5% was obtained except for a region within 2 in of the inner electrode, when the error was −3·5%. This large error was due to the local dissolving out of the graphite or its carrier in electrolyte.

In all these tests the equipotential spacings as plotted on the table were correct so far as could be ascertained by eye from divider measurements between appropriate pencil dot points. This is more than adequate for general engineering investigations, where equipotentials with a positional accuracy of about 1% are required.

To test the ultimate accuracy of the equipment, two accurately machined, parallel and silver-plated brass bars forming a parallel-plate condenser were spaced 9·8 in apart on the 2-dimensional tray. A plot was made of the gradient against probe position for three different tracks between and normal to the electrode surfaces. The mean value of the gradient was 2·04%, with a random spread of approximately ±0·5%, which may have been due to temperature, bubbles or unresolved meniscus effects. The greatest gradient variation occurred at the electrodes in the form of a 1% reduction due to electrode mensicus effects and to perturbation of the field by the probe in the vicinity of the electrodes. The probe was treated with silicone varnish to reduce its meniscus, and possibly the electrode meniscus effects could be removed in a similar manner. The value of the gradient deduced from the 9·8 in electrode spacing and the 0·1976 in spacing of the 2-element probe measured by travelling microscope was 2·016%, i.e. a discrepancy of 1·17% with the value of 2·04% measured electrically.

The above accuracies of ±0·5% were achieved only under ideal conditions after the water had been in the tank for two days, and when all air bubbles had been removed from the electrode and the plate surfaces. This accuracy compares very well with the claims made elsewhere.[5]

For most practical investigations taking into account all defects in model dimensions, it is considered that the repeatable accuracy will not be much better than ±1–2% when measuring gradients as low as 2% of the 100% applied voltage.

(5) APPLICATIONS

The electrolytic tank described has been used for routine 2-dimensional studies of the electric fields in bushings, switchgear and transformer windings and of the potential distribution across individual units of a suspension insulator string. This has followed the work described elsewhere,[3] except that the models have been made on a larger scale.

The deep-tank facility has been used to investigate the 3-dimensional current-flow pattern at the junction of the rotor bars and end-ring of a squirrel-cage induction motor. A further application has been concerned with the pickling process during the continuous production of steel strip in coil form. The speed of the take-up rolls must be controlled in order to maintain the strip at an optimum depth in an acid pickling bath. In this problem, the 3-dimensional variation with depth of the magnetostatic field between the moving steel strip and a speed-control transductor located on the bottom of the lead-lined bath was of interest.

The use of the deep tank for 2- and 3-dimensional problems will now be illustrated in detail by a few typical examples of practical engineering problems.

(5.1) Suspension Insulator String

The potential distribution over a cap-and-pin type suspension insulator string is of great importance in the high-voltage transmission of electrical energy. The aim of the designer is to obtain an approximate uniform potential distribution along the string, either by means of resistance glazing of the insulators or by grading rings or other devices. An alternative method is to

make some of the insulators of high-permittivity material, so that the correct capacitance grading of the potential distribution is achieved. This method is covered by a current Patent application.

As part of a programme aimed at developing such units, some idea was required of the potential distribution along a conventional 275 kV insulator string. With this information, and with further tests, it was expected that a value could be assigned to the permittivity of each insulator unit to give a desirable uniform potential distribution along the string. If the resulting permittivity came within the range of known materials, development could proceed on the manufacture of a suitable unit. Tests could then be made to determine the minimum number of high-permittivity units required to achieve a uniform potential distribution.

(5.1.1) Technique of Representation and Description of Model.

It might have been better to obtain the potential distribution on an actual insulator string rather than resort to model techniques with all the inherent assumptions which have to be made. However, time and expense was limited, and published information with mixed units on line voltages of 220 kV and upwards was rather scanty. Furthermore, the potential distribution for a uniform string is dependent upon the parameter $\sqrt{(C_t/C_u)}$, where C_t is the distributed capacitance to earth to the tower and C_u is the capacitance of each unit. A knowledge of the distribution therefore gives only the ratio C_t/C_u and gives no indication of the individual values of C_t.

The electrolytic-tank model shown in Fig. 5 was made one-

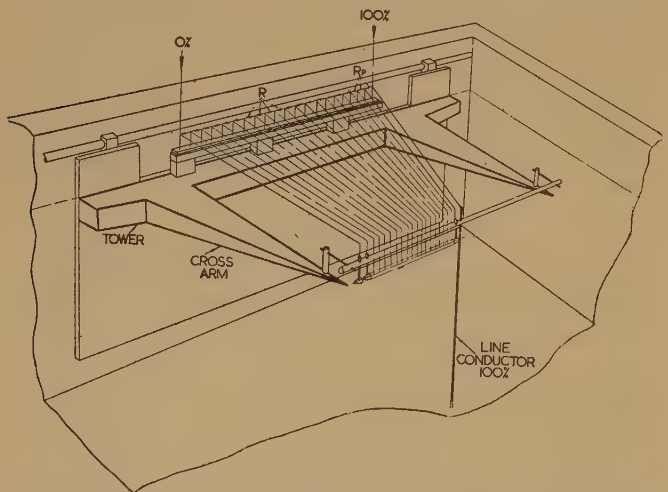

Fig. 5.—Electrolytic-tank model of a suspension insulation string showing the insulator caps, and the representation of the dielectric by shunt resistors.

eighth full size from the appropriate tower dimensions given in a recent paper.[9] Only that portion of the tower included between two cross-arms as indicated in Fig. 5 was included, and full use was made of the two planes of symmetry in the problem. One plane of symmetry cuts the tower along its centre-line into two identical portions having three cross-arms each, while the other plane, which is perpendicular to the first, cuts one of these portions into a further two similar sections. This technique allows a larger-scale model to be used in a bath of fixed dimensions. No account was taken of the asymmetry introduced by the cross-bracing struts of the tower, and these were represented by continuous silver-plated brass sheet which was screwed to an impregnated wooden former. The single transmission line of $0{\cdot}4\,\text{in}^2$ section was represented to scale by a small-diameter vertical brass rod running the whole depth of the tank.

Since it is impossible at the present stage of development to represent the porcelain dielectric of the insulators, shown dotted in Fig. 7, in the electrolytic tank in 3-dimensional form, only the metal caps of the insulators were represented, as shown in Fig. 5. Only one-half of each of the 20 caps was submerged in the water, and provision was made, as shown in Fig. 5, for the connections to the resistors R between the caps. By the simple expedient of connecting appropriate resistors between the caps it was hoped to simulate dielectrics of different permittivity.

(5.1.2) Measurement of the Capacitance between Units.

The first step in the investigation was to measure the effective capacitance between the caps of successive insulator units without the porcelain dielectric being represented. This was done by measuring the analogous conductance between the caps in the tank. A concentric-cylinder electrode system of known radii and electrolyte depth, and therefore of known effective capacitance, was placed in a remote corner of the tank and connected across the pulse supply in series with the connections to two adjacent caps on the model. The relative division of the supply voltage between the concentric cylinders and between the caps indicated that the capacitance between the caps was $0{\cdot}08\,\mu\mu$F. Since only half of each cap is submerged, the total capacitance should be increased to $0{\cdot}16\,\mu\mu$F—this, of course, assuming air dielectric between caps.

A further factor to be accounted for is the scale factor of $\frac{1}{8}$, which would indicate a full-size eightfold increase in the $0{\cdot}16\,\mu\mu$F capacitance to $1{\cdot}28\,\mu\mu$F with air dielectric. This figure is only $0{\cdot}0197$ of the $65\,\mu\mu$F which is the approximate measured capacitance of a standard 275 kV glass cap-and-pin suspension insulator unit. The conductance between the caps must therefore be increased, and it was found that the resistances R must be reduced to 300 ohms in order to represent correctly a unit of $65\,\mu\mu$F capacitance. This takes into account the dielectric constant of the glass, of about $6{\cdot}5$, and also the increase in capacitance between the units due to the pin, which was too small to be represented accurately.

(5.1.3) Comparison of Potential Distribution obtained by Direct Measurement and with Electrolytic Tank.

Fig. 6 shows a comparison between the electrolytic-tank results using equal shunts ($R = 300$ ohms) and the results obtained by direct measurements at high voltage on an actual insulator string (supplied by Dr. Forrest of the Central Electricity Authority). Values of percentage potential to earth are shown plotted against percentage string distance from the line at 100% potential to the earthed tower at 0% potential. The agreement is reasonable, bearing in mind the many errors which could arise. It is perhaps of interest to note that the electrolytic-tank results may confirm in an indirect manner that the presence of the test leads across an insulator-string unit does not introduce any serious errors when the voltage distribution is being measured directly at high voltages. This can be inferred, since the test leads in the electrolytic analogue can have no effect on the distribution.

Fig. 7 shows one of the typical field plots obtained during the investigation.

(5.1.4) Potential Distribution with High-Permittivity Units.

The above preliminary experiments indicated that a desirable uniform potential distribution could be obtained by reducing the 300-ohm shunts along the whole string to 22 ohms. This implied an increase in permittivity of 300/22, i.e. $13{\cdot}6$, times the normal value of 6–7 for all the units. The material most likely to satisfy this condition is Rutile,[10] which has a permittivity of 100, i.e. 100/7, or 14, times that of porcelain.

The use of a complete string of high-permittivity units is obviously uneconomic, and experiments were then directed to

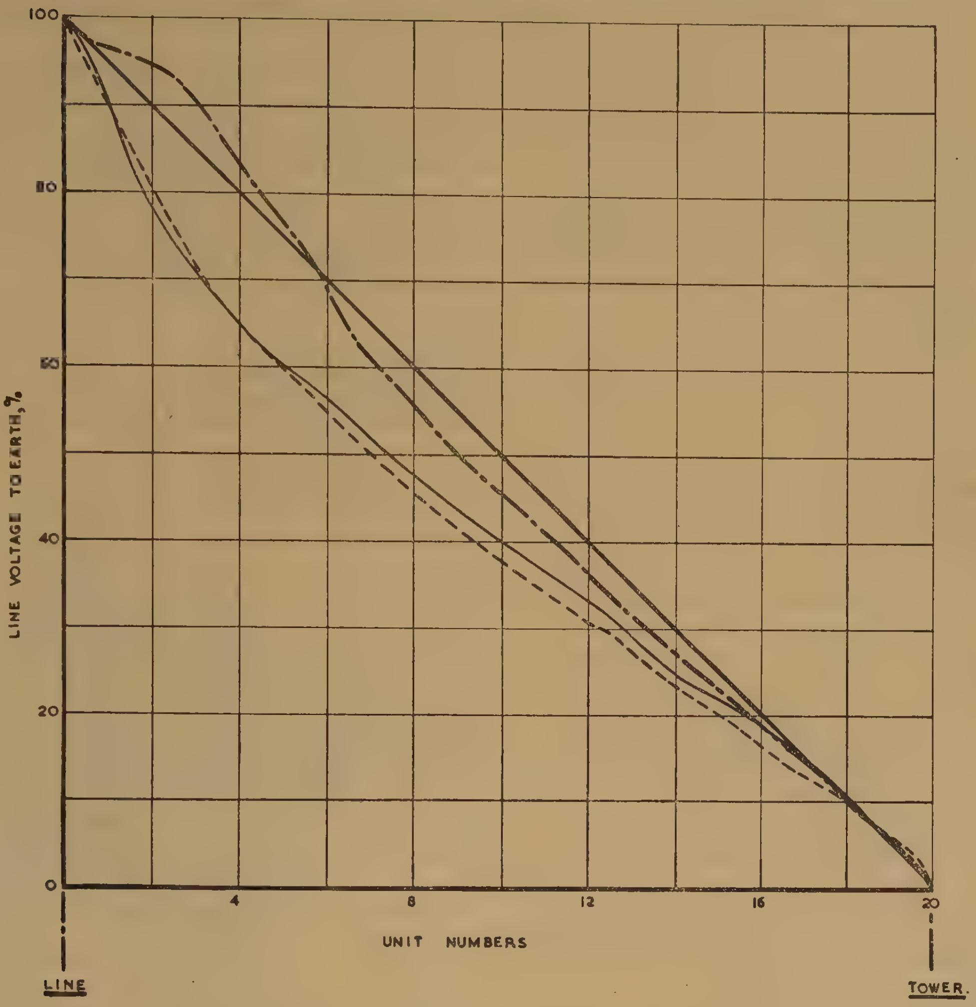

Fig. 6.—Potential distribution on a suspension insulator string.
——— Curve derived from C.E.A. test measurements, rural conditions.
– – – – Curve derived from electrolytic-tank measurements for a uniform string.
—·— Electrolytic-tank measurements with three high-permittivity units at the line end.

putting various numbers of high-permittivity units at both the line and the tower ends with intermediate normal units. The best results were obtained with only three high-permittivity units, R_p (Fig. 5), at the line end, as indicated by the broken line in Fig. 6: with less than three units at the line end there were still fairly high gradients in that region; with more than three units these gradients were substantially reduced, but at the expense of an undesirable increase on the remaining normal units.

The work has indicated that a substantially uniform potential distribution can be obtained over a high-voltage suspension insulator string consisting of 20 cap-and-pin units by using three high-permittivity units at the line end. Rutile, with a permittivity of 100, would probably be a suitable material from both electrical and mechanical considerations. The electrical and mechanical tests which such an insulator must withstand are outlined in B.S. 137: 1941.

(5.2) Measurements of the Electric Field Distribution in a Proton Linear Accelerator

(5.2.1) Statement of the Problem.

Linear resonant-cavity accelerators have been built by the University of California to accelerate protons up to energies as high as 32 MeV, and a similar type to accelerate protons to 50 MeV is being built by a British manufacturer in collaboration with the Atomic Energy Research Establishment. The proton-beam behaviour in this accelerator may be investigated with the help of the electrolytic tank.

A general description of the whole linear-accelerator field is given by Miller,[11] while for a more detailed description of resonant-cavity proton accelerators reference should be made to the papers of Alvarez *et al.*[12] A brief description of the operation of such an accelerator is given below.

A smooth-walled cylindrical cavity will oscillate in its fundamental E_{010} mode when the exciting wavelength is $2 \cdot 61$ times the cavity radius. In this mode the electric field is everywhere in phase and its direction is parallel to the cavity axis. The magnitude of the electric field remains constant with axial distance but falls off with radius as a Bessel function of zero order. The magnetic field is distributed about the axis in circles.

If protons are injected along the axis of such a structure, they will be accelerated by the electric field only during similar half-cycles. On alternate half-cycles, however, the field will be decelerating, since its direction is reversed; and for overall acceleration to occur the protons must be shielded from the influence of the field during this time. This is accomplished by introducing hollow tubes along the cavity axis, of appropriate

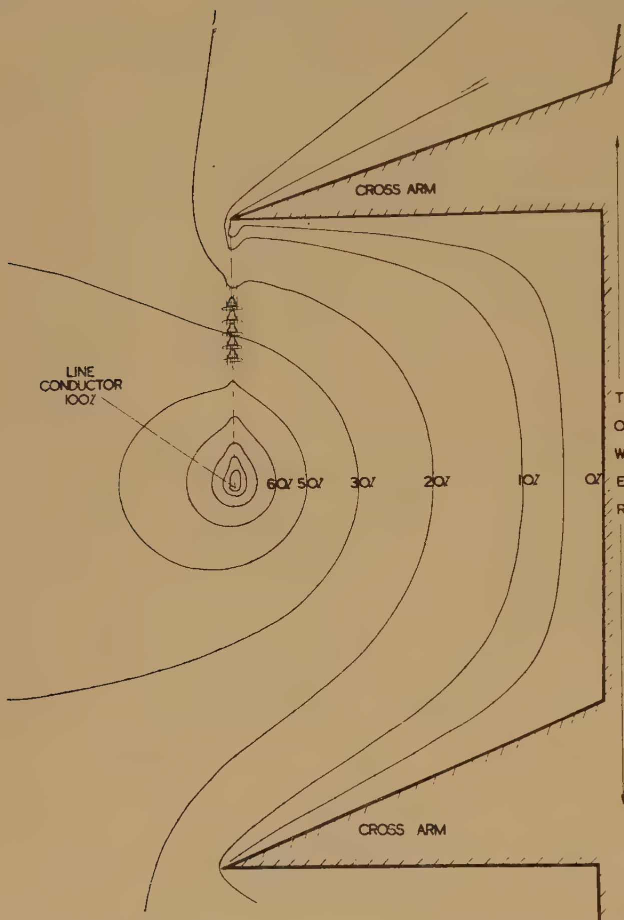

Fig. 7.—Plot of typical potential distribution superimposed on the cross-arm of a transmission-line tower and the cap-and-pin type units comprising a suspension insulator string.

---- Porcelain dielectric.

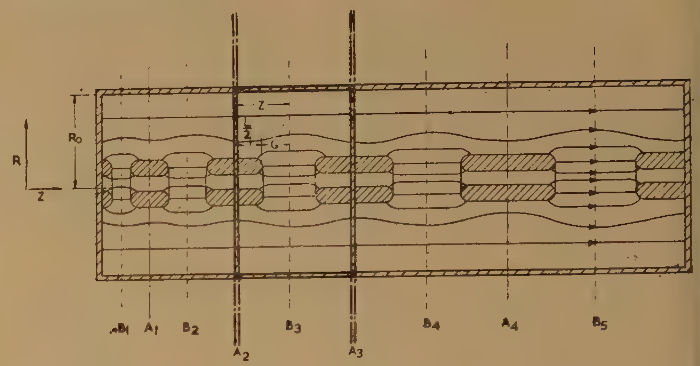

Fig. 8.—Field distribution in a cavity perturbed by drift tubes.

——— Typical unit cell.
– – – – Electrostatic system simulating fields in unit cell.
——— Lines of electric force.
A – – – – – – } Possible planes of symmetry.
B – – – – – –

length and position so that the protons are traversing the fields between the drift-tube gaps only during the accelerating half-cycles. These tubes are termed 'drift tubes' since they do, in fact, allow the protons to drift for a time in a field-free space. The presence of the drift tubes perturbs the field configuration of the smooth-walled cavity in a manner shown in Fig. 8, and as a result, the electric field between the gaps has a radial as well as an axial component.

When protons are continuously injected into an accelerator, not all of them are accelerated. Only those which contrive to cross the drift-tube gaps when the phase of the electric field is correct will be continuously accelerated, and they tend to collect in discrete bunches which travel down the accelerator. The determination of the percentage of injected protons that are bunched, and the conditions necessary to ensure that these bunches are continuously accelerated, becomes a rather complex problem in what might be termed 'proton optics'. Information is also required on the defocusing effects produced by the radial components of electric field mentioned earlier.

To investigate these problems, an analogue computer[13] has been built which requires detailed input information of both the radial and axial components of electric field existing near the axis of the accelerator.

(5.2.2) Simulation of the Electromagnetic Field by an Electrostatic Field.

At resonance, the field configuration within the perturbed cavity is shown in Fig. 8. At certain planes along the cavity, such as A_1–A_4 at approximately the mid-points of the drift tubes, the radial component of the electric field is zero, and conducting planes may be placed in these positions without disturbing the field configuration. The complete cavity may then be considered as several smaller cavities placed in juxtaposition. In Fig. 8 a typical cavity, hereinafter called a unit cell, is shown in heavy lines. The problem is to simulate the electromagnetic field in such a unit cell by an electrostatic field.

The electrostatic system shown in heavy chain-dotted lines in Fig. 8 has a geometry similar to that of the unit cell, except that the walls of the radial transmission line are not short-circuited at $R = R_0$ but are extended to infinity. If now a potential difference is maintained between these 'infinite' walls, the resulting field configuration on the axis will be similar to that for the unit cell. It can be shown by writing down the field solutions for the electromagnetic case that in the gap region the electric field is very much larger than the circumferential magnetic field. If we can neglect this magnetic field, the electric field, E, must satisfy Laplace's equation, i.e. $\nabla^2 E = 0$. Thus the field distribution in the gap for the electrostatic system is very nearly that for the resonant cavity. The identity becomes more correct the smaller the gap width and the larger the outer radius of the cavity. This amounts to the condition that (gap length)/(exciting wavelength) ratio shall be small, since the exciting wavelength is of the same order of magnitude as the cavity radius. The ratio is never greater than 14/150 in the accelerator, and is sufficiently small for the equivalence between electrostatic and electromagnetic systems to hold within the limits of experimental error incurred by the electrolytic tank and measuring equipment.

(5.2.3) Electrolytic-Tank Models.

The electrostatic system for a gap may take the heavy chain-dotted form shown in Fig. 8.

With this system, which possesses rotational symmetry about the axis, it is possible to simulate the configuration using a wedge tank.[1,16] The disadvantages with this method, however, are the surface-tension effects at the 'shore line' where the inclined base breaks the water surface. The shore line is therefore ill-defined, and the field in this region, which is required to a high degree of accuracy, is distorted. If, however, a complete half-section is immersed in the electrolyte until the free surface of the electrolyte coincides with a diametral plane, the above disadvantages are overcome.

In order to facilitate the manufacture of accurate models and to increase the accuracy of measurement, the actual accelerator electrodes were scaled up four times in the corresponding models. The drift-tube diameters therefore varied from about

1 to 3 ft and the unit-cell widths increased from about 1 to 4 ft progressively along the accelerator.

Some difficulty was experienced initially in constructing such large and accurate models, and while it was possible to cast the model drift-tubes in light alloy, the added complication of patterns and cores and subsequent machining was uneconomical in time and expense. Some success was achieved with turned wooden models, which were waterproofed and then made conducting by means of a chemically applied silver film. A thin metallic layer was then deposited on the models by electroplating with copper followed by silver. Careful impregnation and waterproofing of the wood was required, since the plating was slightly porous and the models were likely to be immersed for as long as a week at a time while measurements were being made. Eventually, the majority of models were made from sheet copper which was spun on to temporary wooden formers. The models were lightly silver-plated to reduce polarization effects as indicated in Section 4.1.

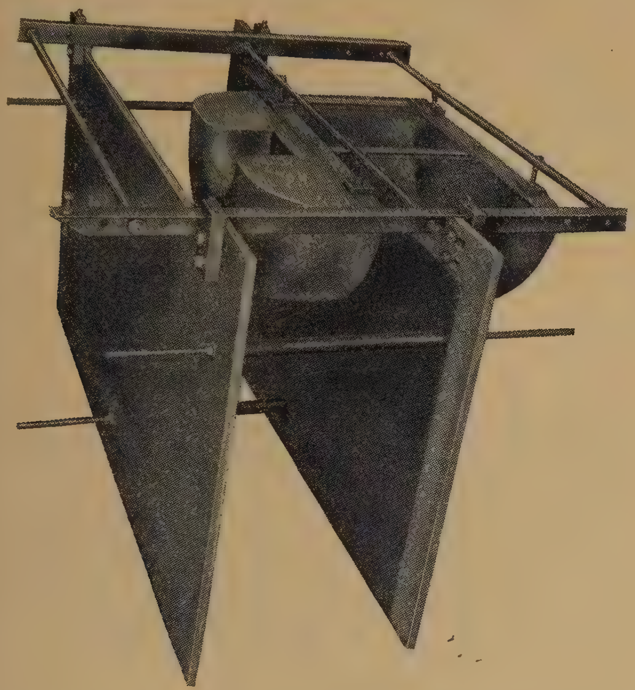

Fig. 9.—Variable model for cavities 2 and 3 of proton accelerator where planes of symmetry are permitted at mid-gap sections.

The accelerator itself consists of three resonant cavities similar to that shown in Fig. 8.

Fig. 9 shows a typical variable model to accommodate all the different gaps in the second and third cavities. The planes of symmetry are made either from Bakelite board sprayed with molten brass, or waterproofed multi-ply wood covered with brass sheet.

(5.2.4) **Method of Plotting.**

Since the components of electric field were required, it was decided to use the double probe (Fig. 2) in order to obtain readings directly proportional to the electric field. This was in preference to using a single probe to determine incremental changes dV in potential for incremental changes dz in distance. If, in the latter method, the component of electric field in the Z-direction, dV/dz, was required to an accuracy better than 1%, then dz must be positioned accurately to 1%. If dz is chosen to be 5 mm, say, a vernier traversing mechanism would be required to set dz accurately to 0·05 mm. Under these conditions, the time taken per reading becomes rather long—a point worth considering in the present case, when many thousands of readings were required.

The actual plots were made by traversing the probe along the axis of symmetry and along paths parallel to this axis but some small distance away. The probe elements were aligned parallel or perpendicular to the axis, depending on whether the axial or radial components of field respectively were being measured.

Figs. 10 and 11 show a few selected plots of the accelerating and radial fields for some gaps in the first cavity. The input

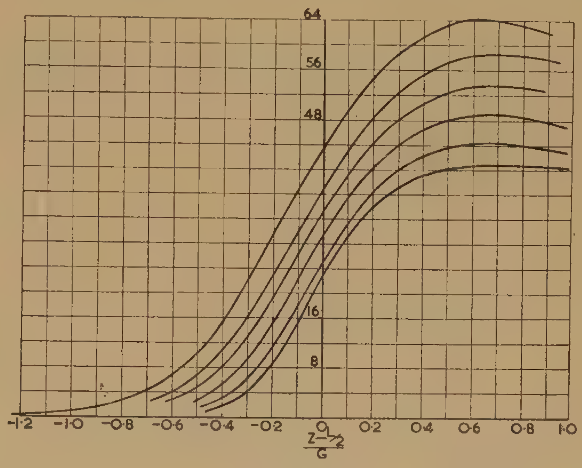

Fig. 10.—Relative axial accelerating fields for different gaps in cavity 1.

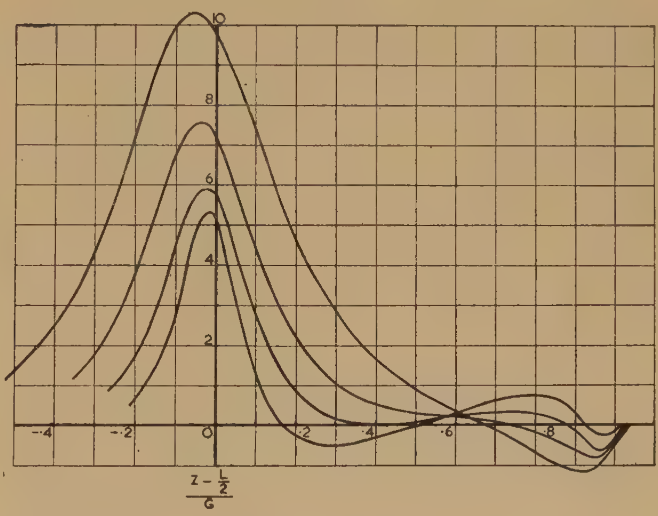

Fig. 11.—Relative radial focusing fields at 0·625 cm radius for different gaps in cavity 1.

information concerning the field distribution is fed to the analogue computer in a graphical form similar to that shown in Figs. 10 and 11. The computer thereafter solves the axial and radial equations of motion and provides data on the proton trajectories.

(5.2.5) **Corrections for Misalignment of the Probe.**

From Figs. 10 and 11 it is seen that, when the radial gradient components E_r are very small, the axial gradients E_z are very large. Consequently, a small misalignment, θ, in the orientation of the double probe when measuring E_r would lead to

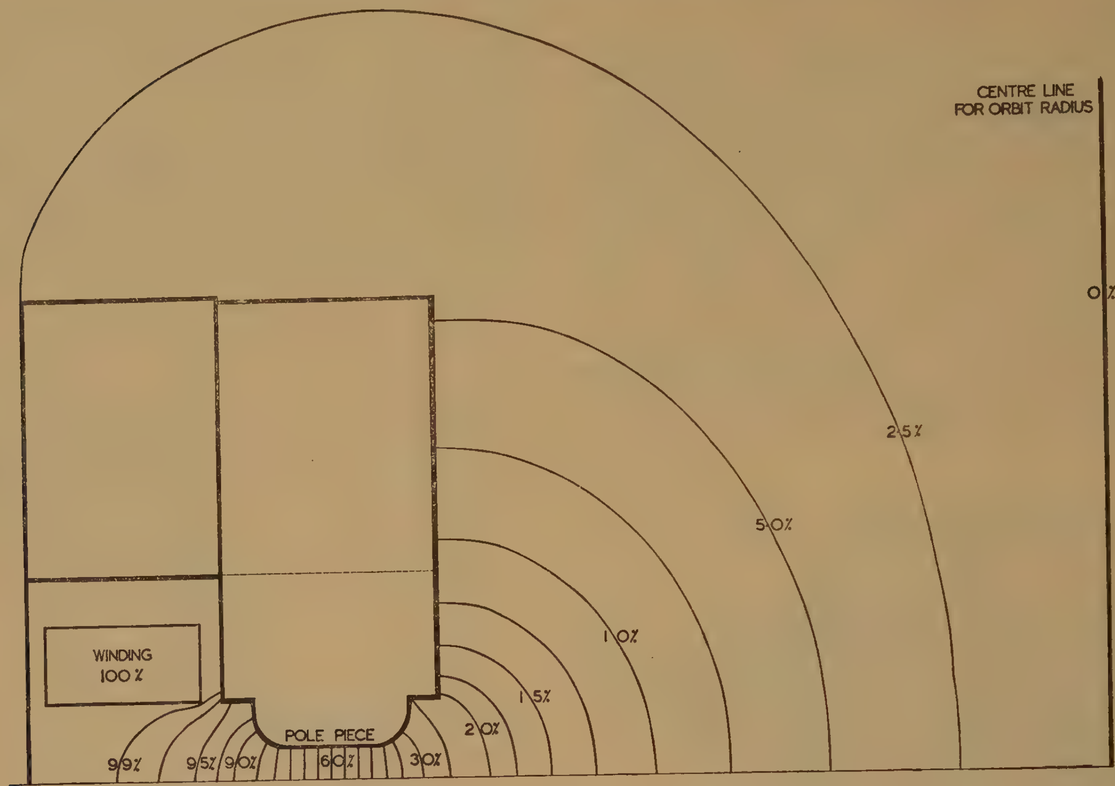

Fig. 12.—Magnetic-flux plot in synchrotron magnet.

a predominant error signal arising from E_z. For precise measurements of E_r, however, the error can be minimized by taking the mean value of individual gradient readings at two points A and B on the true radius equidistant from, and on either side of, the axis. If the line joining the two capillary tubes of the gradient-measuring probe is inclined at an angle θ to the true radius, the individual readings at A and B will be

$$E_{rA} \cos\theta - E_{zA} \sin\theta \text{ at A} \qquad (1)$$

$$E_{rB} \cos\theta + E_{zB} \sin\theta \text{ at B} \qquad (2)$$

The mean gradient E_m derived from eqns. (1) and (2) is therefore

$$E_m = \left(\frac{E_{rA} + E_{rB}}{2}\right) \cos\theta + \left(\frac{E_{zB} - E_{zA}}{2}\right) \sin\theta \qquad (3)$$

Assuming, therefore, that the positioning at A and B is approximately correct, $(E_{zB} - E_{zA})$ and $\sin\theta$ are both nearly zero, so that their product in the final term of eqn. (3) is very much smaller than the corresponding individual error terms, $E_z \sin\theta$, in eqns. (1) and (2).

(5.2.6) Conclusions.

The above example illustrates how, under certain circumstances, the solution of an electromagnetic boundary-value problem can be simplified to an electrostatic problem, and how, by choosing suitable planes of symmetry, a complex structure can be divided into smaller, more manageable, structures.

(5.3) Synchrotron Magnet

The present design of electrolytic tank may also be used to study 2-dimensional fields, e.g. the flux paths and magnetic forces which occur in the synchrotron magnet.[15] A half-size electrolytic-tank model utilizing the orthogonal analogy[16] was made to confirm the flux-leakage factor and the magnetic forces involved. Fig. 12 shows a plot of the equipotential lines representing the magnetic flux lines between the opposing poles of one of the 20 C-shaped magnets. The equipotentials are plotted at equal 5% intervals, so that equal amounts of magnetic flux are contained between adjacent lines. It will be noticed that only one-half of the magnet was represented in the tank, since the magnet was symmetrical about the horizontal mid-gap plane.

The flux-leakage factor, defined as (total flux)/(useful gap flux), was calculated from the plot, where it will be seen that there are 8·5 intervals of 5% representing the useful flux over the pole-face. The flux-leakage factor is therefore 20/8·5, or 2·35. The measured leakage factor on an actual small-scale model was 2·3. The agreement is fairly good, bearing in mind that in the synchrotron 20 of these C-shaped magnets were arranged in a circle. The electrolytic tank in this case takes no account of the circular symmetry.

The attractive forces on the magnet poles may be evaluated from the knowledge that the working flux density is approximately 10 kilogauss in the mid-polar (approximate) uniform field region. The proportional flux density, B, at all other points along the horizontal mid-gap plane is then calculated and the forces, F, given by $F = B^2A/2\mu_0$ newtons, are evaluated for the particular area $A\,\text{m}^2$ at that point. Calculations give a total force of 80 tons for the 20 magnets. The radial forces on the pole total 2·35 tons, against which suitable bracing was provided in the construction of the magnet.

The above calculations were checked with good agreement by measuring the change of inductance, L, with distance, x, of the interpolar gap. The force, F, is then equal to $\frac{I^2}{2}\frac{dL}{dx}$ newtons.

This was done by arranging for incremental movement of the pole-piece relative to the mid-gap plane, thereby giving the magnetic pull in that direction.

(6) CONCLUSIONS

It is evident that complex 3-dimensional fields defy solution by conventional analytical methods. The extension of the electrolytic tank to solve such problems has therefore been found necessary, and is a logical development in analogue techniques.[8]

The deep tank and its associated electronic equipment is capable of the accurate solution of complex 3-dimensional fields in addition to the large-scale and more detailed study of 2-dimensional fields. The technique has been illustrated with reference to a few typical engineering problems. A further development which is now required is a suitable thin conducting boundary layer for separating electrolytes of different conductivity, so that complex 3-dimensional problems with mixed dielectrics may be studied.

(7) ACKNOWLEDGMENTS

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DISCUSSION BEFORE THE MEASUREMENT AND CONTROL SECTION, 9TH APRIL, 1957

Mr. J. G. Yates: I have been interested in the use of electrolytic tanks for some ten years, since my colleague, Dr. Sander, began using them as part of a system for tracing electron trajectories. We first thought that they were simple things to use; we have since learnt that much careful work is necessary to produce a reliable tool. Once one has taken the necessary trouble, the use of electrolytic tanks can give accurate results in a wide range of problems.

There are a number of points of technique raised by the authors. First—without wishing to raise an old controversy—I should be interested to know the resistivity of the Manchester tap-water. We find that a value of about 10^4 ohm-cm is suitable for our system. This is a compromise between not having it too large, which makes the probe impedance too high, and not having it too low, which increases the difficulties caused by polarization at the tank electrodes. Since Cambridge tap-water has a resistivity of about 2500 ohm-cm, we use a commercial deionizer to reduce the conductivity and then bring it to the desired value by the addition of a drop of acid or a proportion of tap-water.

In order to avoid emptying the tank frequently for cleaning, we found that a drop of wetting agent let fall on the surface sends dust particles shooting to the side of the tank; in addition, we use a miniature vacuum-cleaner, consisting of a filter pump and nozzle, to clean the surface.

I congratulate the authors on the use of a ring of silicone varnish just above the tip of the probes to reduce the variation of meniscus height. We had used a silicone water-repellent over the whole of the probe, without success, and were driven, because of errors caused by meniscus variation, to a more radical solution,* in which, in effect, we turned the whole system upside down and made the measurement in the plane of the bottom of the tank, using capillary probes flush with the bottom surface. This eliminates the errors due to the meniscus and provides a virtually unbreakable probe-array, but the system cannot be used for 3-dimensional measurements and has certain other drawbacks.

* Sander, K. F., and Yates, J. G.: 'A New Form of Electrolytic Tank', *Proceedings I.E.E.*, Monograph No. 195 M, September, 1956 (104 C, p. 81).

We have not recently used a colloidal graphite coating on electrodes, because we found that this served only to protect the electrodes from corrosion. Instead, we prefer to use a material which does not corrode, such as stainless steel or chromium plate, for the electrodes.

Is there any real advantage in using an unequal mark/space ratio for the tank excitation? We prefer to increase the operating frequency to as high a value as is consistent with the decay of the initial spikes. Increasing the length of one-half of the rectangular wave reduces the slope on this, owing to polarization, but it increases the slope on the remaining short period, so that the improvement in accuracy, if any, is small.

We have continued to use transformers in the measuring circuits, because we find that a suitable tapped transformer is a very effective device for obtaining the actual measurement reading. A 2-decade tapped transformer and a slide-wire enables settings to be made to 1 part in 10^4 and costs much less than a resistance box of similar accuracy.

I should like to ask two questions on the use of the electrolytic tank. First, what is the nature of the analogue computer used by the authors for obtaining electron trajectories from measured field plots? I am interested to know whether this provides a simpler and cheaper apparatus than our present method of using a computer coupled to the tank itself in order to trace the trajectories directly. Secondly, have the authors any views on the sort of problems in which a resistive network analyser shows advantages over an electrolytic tank for field measurements?

Mr. J. W. Gallop: I, too, suffered from the delusion that an electrolytic tank was a very simple piece of equipment that could be set up quickly in a laboratory to solve the problem on hand. The authors completely shatter this delusion, and demonstrate that it is really a major engineering project.

I am interested in the authors' reasons for setting up an electrolytic tank in the first place, namely to solve some of the field problems associated with the proton linear accelerator, and I am wondering why they made the choice. If there are a number of problems that will keep the tank in almost continuous use, the choice is fairly obvious; but if the problems are not so numerous and, perhaps, more varied, I should have thought that the relaxation techniques as exemplified by Southwell* were more powerful in some respects. As the authors form part of a computer group, I should like to know whether they have considered this aspect of the problem. To be specific, do they think that it would pay a small laboratory to incur the expense of a tank, or would it be better to train somebody in relaxation techniques? As an example I have very much in mind our experience at Hammersmith, where we started to set up an electrolytic tank for solving some of the problems associated with the cyclotron but eventually went over to relaxation techniques. In our case I think this was a wise move, since it enabled us to deal with some problems of beam dynamics which I do not think could have been solved by means of the tank.

Mr. J. K. Webb: No mention has been made by the authors of the alternative method of solving the Laplace equation by means of a rubber model.† There is one way in which such a model can be used which I have never seen mentioned in the literature on the subject and which has the great advantage of being free from frictional effects and giving an immediate picture of the configuration of the field without the necessity of plotting it point by point. This is to locate equipotentials by observing the contours obtained by projecting a parallel shaft of light, which has been 'ribbed' horizontally, across the surface of the model. The optimum layout may thereafter be determined by trial and error. I suggest that this method might at least prove a useful adjunct to that of the authors, whose comments would be appreciated.

Mr. P. A. Einstein: I am interested in the problem relating to the field near the insulator, and believe that it might be possible to obtain a more exact solution by replacing the insulator, not by an insulating material in the tank itself, but by some conducting material which bears to the tap-water a conductivity ratio equal to that which the insulator material bears to the air in terms of dielectric constants. Are the authors aware of any material which might be used for such a purpose? I think the difficulty is probably in finding or manufacturing a material which has just the right conductivity; there may possibly be a way out by moulding, say, Perspex with, perhaps, an inclusion of metal filings, or even making a hollow shell whose walls are punctured by a series of holes containing metal rivets. The inside of this shell would be filled with a dielectric material such as copper-sulphate solution, the conductivity of which can be controlled quite easily, and, in addition, would permit the field to be mapped inside the insulator material.

Mr. P. H. G. Allen: If a sinusoidal a.c. supply is employed, the Boucherot circuit* can conveniently be used for injecting prescribed currents into the electrolytic tank. This consists of an inductor and capacitor (L and C_2 in Fig. A) resonant at the working frequency and having a high Q-factor. The output current, I_2, is proportional only to the voltage, V. Supplying groups of such circuits at common input voltages, V, provides suitable current injection for magnetic-field plotting. In this way, large percentages of the available voltage are not lost in high resistances, and greater accuracy is achieved in the representation of the field within the winding. The voltage in the tank is controlled, for a given current level, by adjustment of the electrolyte conductivity. We find that a mixture of equal parts of Rugby tap-water with distilled water gives suitable results. Polarization voltages are a function of current level, and higher voltages minimize such errors.

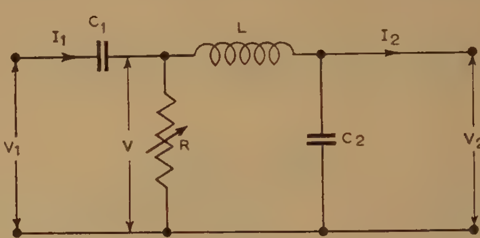

Fig. A.—Controllable constant-current circuit.

A variation, where individually controllable currents are required (such as in space-charge fields†), is given by the complete circuit‡ shown in Fig. A ($C_1 = C_2$). Here, provided that $V_2 \ll V_1 - V_2$, changes in output current are proportional to R and are practically unaffected by V_2 or by variation of other source currents. Currents can be metered in terms of V.

* SOUTHWELL, R. V.: 'Relaxation Methods in Theoretical Physics' (University Press, Oxford, 1946).

† WALKER, G. B.: 'Factors Influencing the Design of a Rubber Model', *Proceedings I.E.E.*, Paper No. 821 M, April, 1949 (96, Part II, p. 319).

* BOUCHEROT, P.: 'À propos des systèmes U_1/I_2 = constante', *Revue Générale de l'Electricité*, 1919, 5, p. 203.

† BAKER, B. O.: 'Plotting Electron Trajectories in Space-Charge Fields using the Electrolytic Tank', *Proceedings of the International Analogy Computation Meeting*, September, 1955, p. 314.

‡ ALLEN, P. H. G.: 'The Distribution of Temperature in a Layer-Type Transformer Winding', *Proceedings of Third B.T.H. Summer School*, 1956, p. 47 (British Patent Application No. 7991, 1956).

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. E. R. Hartill, J. G. McQueen and **P. N. Robson** (*in reply*): We are interested in Mr. Yates's and Mr. Allen's experience of tap-water in Cambridge and Rugby, which are apparently hard-water districts in which the water resistivity is about 2 500 ohm-cm. It would appear from Mr. Yates's remarks that we are fortunate in being able to use Manchester tap-water, which is notoriously soft and has a resistivity of $10-15 \times 10^3$ ohm-cm.

In reply to Mr. Yates, the general-purpose (proton or electron) analogue computer* was part mechanical and part electrical by nature. It was used to determine the phase relationships and radial motions of the protons, which are more complex than those of conventional electron optics. The electric fields vary in both time and space, and there is a superimposed magnetic field to be taken into account, in addition to the relativistic increase in proton mass. Such corrections cannot be taken into account with a trolley coupled to the tank, so that any comparison of costs is rather meaningless.

The use of an unequal mark/space ratio for the tank excitation is an advantage. Increasing the length of one half of the rectangular wave can double the polarization slope only during the short period, while the slope during the long period can be made as small as desired. If the balance is achieved by observing the back edge of the current pulse, it is the very low polarization slope which affects the setting. The single precision resistance box facilitates rapid setting and eliminates any doubts about accuracy.

The resistor network mentioned by Mr. Yates probably has an advantage over the electrolytic tank for those 2-dimensional problems in which the boundaries consist of straight lines or right-angled bends,† and when multiple plots are required. There is not much to choose between the accuracy of the two methods: the inherent disadvantages of using an electrolyte are probably as great as the limitations due to finite mesh size in the resistor network. The resistor network, however, cannot easily be applied to mixed-dielectric or asymmetric 3-dimensional problems.

We agree with Mr. Gallop that in the absence of a tank the Southwell relaxation method is more economic for single plots. For multiple and routine field plotting, and particularly for 3-dimensional fields, a tank is essential. The rubber-sheet and parallel-shaft-of-light method mentioned by Mr. Webb has recently been used* by our organization in connection with the design of electron guns.

In reply to Mr. Einstein, we have no information on conductivity materials which could be used for simulating insulator materials. His suggestion regarding the use of thin, hollow insulating shells with metal rivets has, however, been covered by British Patent No. 693782, 1951, and the method was used in investigations concerned with oil and natural-gas prospecting.

Mr. Allen's technique of current injection is very ingenious, but, unfortunately, we cannot take advantage of this method with pulse excitation. We have recently found, however, that sufficient accuracy can be achieved by using resistors in the conventional manner with an equal division of the supply voltage across the pool and combined series resistors. The problem was concerned with the 2-dimensional distribution of slow-neutron flux over the cross-section of various shapes of uranium fuel elements in a nuclear reactor. For the particular case of an element of square cross-section, which is amenable to calculation, the tank results agreed within 2%. The model was about 2 ft square and $1\frac{1}{2}$ in deep, and had about 200 probes to represent the uniformly distributed slow-neutron sink afforded by the cross-section of the element. The probable reason for the agreement is that the resistances through the electrolyte from the relatively small-diameter probes are nearly independent of their position in the pool.

* CROWLEY-MILLING, M. C.: 'A Computer for Solving some Problems in Connection with Travelling-Wave Particle Accelerators', *Journal of Scientific Instruments*, 1934, 31, p. 100.

† LIEBMANN, G.: 'The Change of Air-Gap Flux in Electrical Machines due to the Displacement of Opposed Slots', *Proceedings I.E.E.*, Monograph No. 208 M, November, 1956 (104 C, p. 204).

* ALLEN, K. R., and PHILLIPS, K.: 'Use of a Rubber Sheet Model for the Investigation of Electron Trajectories', *Electronic Engineering*, 1955, 27, p. 82.

DISCUSSION ON 'RESISTANCE HEATING OF MILD-STEEL CONTAINERS AT POWER FREQUENCIES'*

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 4TH FEBRUARY, 1957

Mr. R. D. Haigh: In the examples given in the paper it is assumed that the power required in the work is known. Unfortunately, this information seems difficult to ascertain in practice, and the author's suggested methods of providing tappings either on the transformer or the heating coil are therefore very essential.

There is no indication of the type of insulation used on the wire with which the inductive heating coils are wound. Although the temperature at the surface of the lagging round the vessel should not be very high, it will presumably be desirable to use some heat-resisting material as insulation. Has the author any recommendations on this matter?

In Section 5.1 the author states that the area enclosed by the pipe and the return cable should contain no ferrous material and should be a minimum. I presume that this is to reduce the reactance added by the return path, and can see that the presence of ferrous material will exercise an appreciable effect. But will not the effect of increasing the loop area be negligible compared with the reactance of the rest of the circuit?

In Section 5.2 it is stated that the Curie point represents the limit of both conductive and inductive heating. In conductive heating, will there not be a fall in the reactance of the external circuit which will increase the current and thus to some extent offset the loss of heating effect as the pipe becomes non-magnetic?

In conductive heating of flanged pipes, what method of bonding across flanges is adopted, and what precautions have to be taken to insulate the pipe from its supports to avoid leakage paths?

Where suitable steam supplies are readily available and where the required temperature is not too high, steam tracing is comparable in installation cost with electric heating; from data I have obtained it appears that running costs for steam are about one-quarter of those for electrical heating, but I should like the author's views on this.

* THORNTON, C. A. M.: Paper No. 1230 U, April, 1952 (see 99, Part II, p. 85).

In the formulae for inductive heating I have endeavoured to determine the effect of a change of lagging thickness, beyond affecting the ohmic loss due to the change in winding resistance. Is it correct to assume that there is negligible change in the heating effect over the range of lagging thickness normally encountered?

The author states that his formulae do not apply to the heating of small vessels of domestic size. Apart from this, would not the normal contact or immersion-heating elements be more economical for such applications?

Mr. C. A. M. Thornton (*in reply*): The cable employed for inductive heating coils has generally been mounted outside the lagging, in a comparatively cool situation; asbestos-based insulation has been used, the cables being in air on a framework of synthetic-resin-impregnated wood which permits free ventilation and inspection. The area of the loop enclosed by the pipe and the return cable seriously affects the constants of the circuit where—as in conductive heating—low voltages and high currents are employed.

There are now good textbooks* on the subject of inductive heating of ferrous vessels above the Curie point as well as non-ferrous vessels at power frequencies. It was estimated that a coil of 60 turns would be required to dissipate 100 kW at 480 volts, 50 c/s, at 900° C in a mild-steel vessel 2 ft × 2 ft × 2 ft, and that the power factor would be about 0·4. The same coil would dissipate 65 kW in the vessel when cold, falling to about 30 kW below the Curie point. A tapping at 44 turns would probably be more convenient for heating this vessel below the Curie point.

We avoid flanged pipes whenever possible in conductive heating, for flanges produce cold spots unless heavily lagged. Non-metallic packing has not been used, and bonding has therefore not been necessary.

The relative costs of steam and electric heating vary so much according to circumstances that it would be unsafe to generalize, but we do not regard them as competitive. We use steam heating within its limitations and electric heating outside these limitations, chiefly above 200° C.

There is an optimum lagging thickness calculable from formulae supplied by lagging manufacturers. We use this thickness and wind coils outside it. The lagging thickness affects the power factor of the load, not the power input for a given heat dissipation in the vessel. It is possible to wind coils close to the vessel walls for optimum power factor and cover overall with lagging, but the coil insulation must then withstand the much higher temperature close to the vessel wall and the coil is not accessible for inspection.

Immersion-heating elements of small thermal capacity are very economical, but I think there is a future for inductively heating ferrous vessels in the domestic field. The ideal domestic cooker of the future will combine all known methods of electric heating each in its best application.

* STANSEL, N. R.: 'Induction Heating' (McGraw-Hill, New York, 1949), p. 102.
MAY, E.: 'Industrial High-Frequency Electric Power' (Chapman and Hall, London, 1949), p. 175.

DISCUSSION ON 'TIMING THE OPERATION OF CONTROL SYSTEMS ASSOCIATED WITH ROTATING EQUIPMENT'*

WESTERN UTILIZATION GROUP, AT CARDIFF, 28TH JANUARY, 1957

Mr. C. E. Dew: The paper illustrates once again the close harmony and liaison which exists between industry and the Factory Department of the Ministry of Labour and National Service, and it is felt that this willingness on the part of the various factory inspectors to come to the aid of works engineers in seeking a solution to a problem should be given wide publicity.

The paper is primarily concerned with the stopping of rotating equipment by a number of methods including the use of electro-mechanical brakes. In my opinion brakes should only be used in a limited field, for example on crane work where it is required to hold the load or on installations similar to those described in the paper, i.e. continuously rotating equipment where the brake is required for additional retardation in emergency stopping.

The use of electro-mechanical brakes on continuous rapid-reversal heavy drives, as found in steelworks, is open to question, since the motor and brake assembly may contribute 90% of the total rotational inertia, and of this figure as much as 30% may be contributed by the brake drum. Furthermore the brake mechanism is subject to rapid wear and tear involving a continual adjustment to varying standards, which has led to the practice in the organization with which I am connected of omitting the brake wheel from reversing drives and relying entirely on plugging.

Where braking assemblies are essential, however, consideration may be given to the use of recently developed materials such as Mehanite and to the use of brakes having a minimum of linkages. The motor itself, if used on direct current, should be designed for the lowest voltage in order to take advantage of the lower ratio of diameter to length and consequent reduction in rotational inertia.

Would the authors confirm that the practice for this type of plant conforms with their experience, and have they any comments to make on brake mechanisms employing a minimum of linkages, the use of Mehanite for the brake drum and the use of low-voltage direct current to obtain the best ratios of diameter to length?

Messrs. C. Cuthbert and D. A. Picken (*in reply*): The recommendations made in the paper are not necessarily valid outside the field in which they are made, namely the application of braking devices to rubber rolls and similar operations.

It is agreed that after continuous use alternative techniques may show an advantage, but so far as wear of the braking surfaces is concerned this should not give rise to difficulties, although on frequently-repeated operations wear on linkages might well become a serious problem.

The authors have not had experience of Mehanite, or of the use of low-voltage direct current to improve the ratio of diameter to length, although obviously in the latter connection reduction in voltage will permit a reduced number of commutator segments to be used and so will improve the ratio.

* CUTHBERT, C., and PICKEN, D. A.: Paper No. 1800 U, March, 1955 (see 103 A, p. 112).

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The Institution of Electrical Engineers
Paper No. 2284 U
Feb. 1957

DEVELOPMENT OF TRANSPORTABLE THERMAL-STORAGE SPACE HEATERS

By E. BATES.

(*The paper was first received* 14*th September, and in revised form* 31*st October*, 1956. *It was published in February*, 1957, *and was read before the* NORTH-EASTERN CENTRE 25*th February, and the* UTILIZATION SECTION 11*th April*, 1957.)

SUMMARY

Reference is made to the shortage of generation, transmission and distribution capacity following the end of the 1939–45 War and upon the resumption nationally of normal activities. This prompted a renewal of interest in the storage of energy in the form of heat, and the paper describes briefly experiments that were made leading to the design and production in this country on a commercial basis of transportable unit-type thermal-storage space heaters.

The suitability of buildings for this form of heating is discussed, as also are methods of planning and controlling installations.

In forecasting the future of this form of heating there is reference to electricity tariffs and to the relative costs of electricity and other forms of fuel.

(1) INTRODUCTION

The coal shortage experienced during the winter of 1946–47 was a national disaster, but to the electricity supply industry the inadequacy of plant to meet consumers' demands presented an even greater problem in the subsequent winters. During the war years almost no new plant had been installed; even the maintenance of existing plant had been curtailed to the minimum.

The gearing-up of peace-time production, urged by the greatest-ever need to export manufactured goods, resulted in a growth of load at a rate faster than new generating plant could be made and commissioned. This was, moreover, accompanied by a tendency to reduce working hours and to compress them into a five-day week, which further increased the simultaneous demand for power on working days.

Load shedding by voltage and frequency reduction and by 'power cuts' had to be endured in order to avoid widespread breakdowns due to overloading plant.

Demand was noticeably increased in cold weather, and because of this, the use of electricity for space heating received a good deal of condemnation. On the other hand coal suitable for space-heating use was rationed at a low level whilst electricity was being sold at not much above pre-war prices, and these conditions naturally encouraged the use of electricity to an extent perhaps more than normal.

A vigorous programme of extension of generating capacity was embarked on, and it soon became clear that the post-war capital cost of new power stations and plant was at such a high level compared with the pre-war cost that, as the proportion of new plant to old reached a state of dominance by the former, the effect on the cost of electricity would be serious; this in spite of the much improved thermal efficiency of the new plant.

All these things demonstrated the need for close investigation into all possible means of improving the overall load factor of electricity demand, and clearly any steps that would reduce the additional demand caused by space heating during spells of cold weather would be especially efficacious. Such steps would be doubly helpful if the day-time demand so reduced could be transferred to night-time, because, by this means, the revenue would be maintained whilst the cost of the supply would be reduced by the increasingly apparent capital component.

Mr. Bates is with the Eastern Electricity Board.

The extent of idle generation, transmission and distribution capacity during night-time is well depicted by Figs. 1 and 2. Fig. 1 shows a typical winter demand curve in its orthodox form (midnight to midnight) whilst Fig. 2, being from noon to noon,

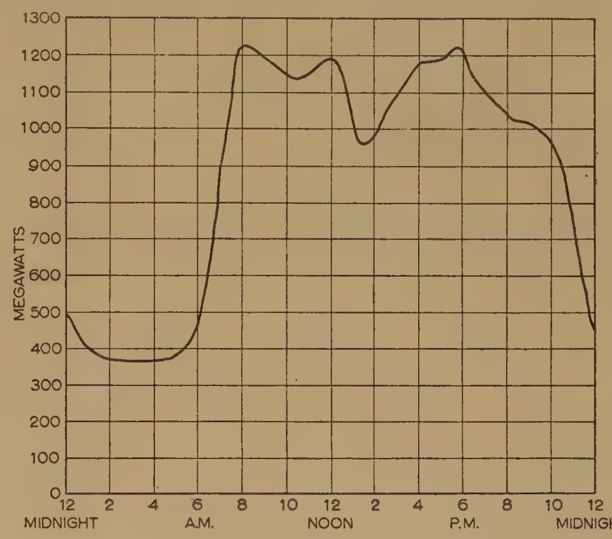

Fig. 1.—Typical winter demand curve.
Midnight to midnight.

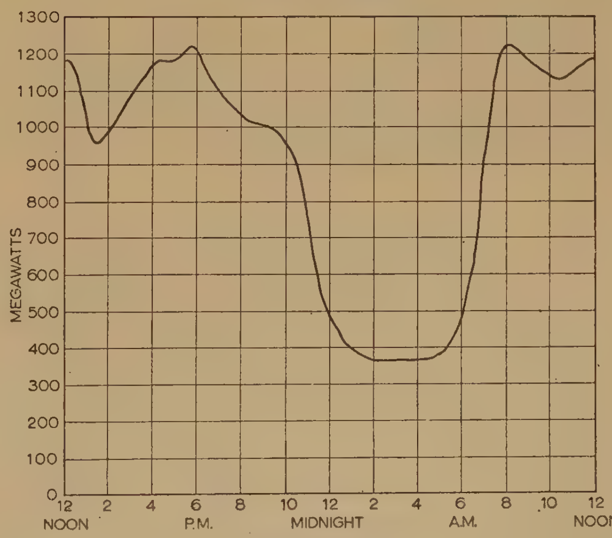

Fig. 2.—Curve shown in Fig. 1, redrawn from noon to noon to emphasize the night valley.

shows the night-time valley unbroken and focuses attention on its depth and duration.

It is not suggested that this is the only or possibly even the most important field by which discrimination in load development can be made to improve load factor in order to offset rising costs,

but no attempt can be made in the paper to deal exhaustively with such a wide subject. The paper has been confined to the possibilities of space heating by means of transportable thermal-storage heaters. There are, of course, other forms of thermal storage, for instance hot water, and semi-storage, e.g. electrically warmed floors.

The paper is, moreover, restricted to the application of the storage heaters to commercial and/or industrial premises, because it is to these that development has until now been directed.

(2) THE POSITION AS REVIEWED IN 1948

As long ago as 1908 a transportable electric thermal-storage heater was patented in this country. In the early to mid-1930's a heater of Swedish origin was available in this country, and although some specimens still exist, they never achieved much popularity, possibly because insufficient attention was paid to automatic control, which, as indicated later, is an essential part of an installation. In addition, and perhaps more significantly, it is only since the recent war that the relative charges for electricity and solid fuel have reached a point where competition for space-heating purposes really exists.

In fairness to the designers and manufacturers, as well as to the progressive supply undertakers who offered attractive off-peak charges, it must be remembered that a number of quite large hot-water storage installations were carried out in the inter-war period, and some of these are still in use.

In certain other countries, mainly in Europe, the spare capacity at night of hydro-electric stations permitted energy to be sold at that time at prices much below day-time levels and competitive with coal and other fuels. In these countries before the war, development of unit-type thermal-storage space heaters had reached a stage of commercial production. Most were designed for a fixed charging period, with some manual control of the rate of heat output by varying the speed of convection. This is fundamentally different from the present approach in this country as will be seen from Section 3.

The storage media employed in Continental models included talc, gravel, fireclay and concrete.

Some experimental installations were completed prior to 1940 in the Republic of Ireland using equipment of Continental origin. When in 1948 the Irish Electricity Supply Board were able to remove a war-time prohibition on electrical space heating, they continued to develop storage methods by unit-type heaters and they subsequently made marked progress.

(3) FIRST EXPERIMENTS

In the Continental designs, manual control was achieved (in differing ways) by varying the area of apertures at the top of vertical channels which passed through the storage mass. This resulted in the delivery of air at temperatures of several hundred degrees Fahrenheit at the outlets, causing stuffiness and the presence of 'scorched dust' in the air. Because of this it was decided to approach the design of equipment with the aim that the control of installations should be automatic in all respects and that no reliance should be placed on the willingness or ability of the user himself to perform any manual regulation, and that high surface or air temperatures should be avoided. This meant that control must be by a variable input of energy with discharge occurring at a natural rate.

Ideally the heat-storage medium should be of material whose characteristics include high specific heat, low thermal conductivity and, if it were a natural combination, low specific weight; this is on the assumption that it is intended to go through the heating and cooling cycle without a change of state. Other considerations in the choice of materials are cost, availability, ease of handling, freedom from odour and that the material shall be reasonably non-hygroscopic.

As a first experiment a heater was constructed early in 1949, using as a shell a standard 40 gal tank of the type used for domestic hot-water storage and having dimensions of 1 ft 8¼ in × 1 ft 8¼ in × 2 ft 3 in high. Welded to the bottom of the tank were four tubes of 2 in diameter standing vertically with caps welded over their upper ends, and into these were inserted elements of the 'removable core' immersion-water-heater type so arranged and connected as to produce a total loading of 1 kW. At heights of 6, 12 and 18 in from the bottom of the vessel, groups of three thermometer pockets were mounted in a horizontal plane. The pockets were arranged so that the metal inner extremities were insulated from the surface of the vessel in order to prevent these becoming a ready conduction path. Each group of pockets comprised one 3 in long, one 6 in long and one extending to the centre of the tank. The tank as adapted was raised from the floor and supported by a framework or stool of mild-steel angle. The space between the elements was then loaded with sand that had previously been dried as much as possible.

It was realized that this first attempt was in a form that had no commercial possibilities, but it was desired to test certain aspects, namely the suitability of sand as a storage medium, and the relationships between mass, surface area, heat energy stored, surface temperature and rate of discharge. By the use of the thermometer pockets it was possible, too, to observe the temperature gradient from that part of the material nearest the elements towards the surface. As expected, temperatures of the order of 450° F were present adjacent to the elements, falling in an even gradient to an average of 140° F on the surface.

Observation of these various aspects indicated that if the same or improved characteristics could be achieved in a heater of a more appealing shape and appearance commercial development might follow.

Accordingly, and with a view to obtaining actual experience in use, a batch of 12 heaters was made, of modified design having dimensions 2 ft 3 in wide × 11 in deep × 2 ft 6 in high. Four elements in tubes (total loading 1 kW) were mounted from a 'false floor' located 6 in above floor level. These heaters were filled with boiler-wall bricks (used ones taken from a power-station boiler during maintenance), and the spaces between the bricks were filled with dried sand. The use of boiler bricks was introduced because sand would clearly be most inconvenient on any large scale (not the least difficulty being that of drying it). In the space beneath were housed the main terminals and internal wiring as well as the head of a stem-type domestic-oven thermostat. This, with its active rod immersed in the sand between the bricks, was introduced to prevent overheating in the event of a heater being left in circuit continuously owing to failure of the time switch or other automatic control gear, and it was also desired to test the variable setting of such a thermostat as a means of control.

Although a loading of 1 kW was retained in these modified models the storage contents were somewhat less, since it was realized that a higher surface temperature was admissible.

With these heaters it was decided to heat certain office rooms during the winter of 1949–50, and to observe the results achieved. Some six offices were chosen, but particular attention was paid to the results in two of them, one having a south aspect and the other a north one. A variety of instruments was employed. It is not proposed to describe at length all the information that was recorded, but rather to refer to the conclusions reached. Control of the heaters was by time switch only plus the small element of thermostatic control introduced by the internal oven-type thermostat.

Figs. 3(*a*) and 3(*b*) are interesting in that they show the recorded

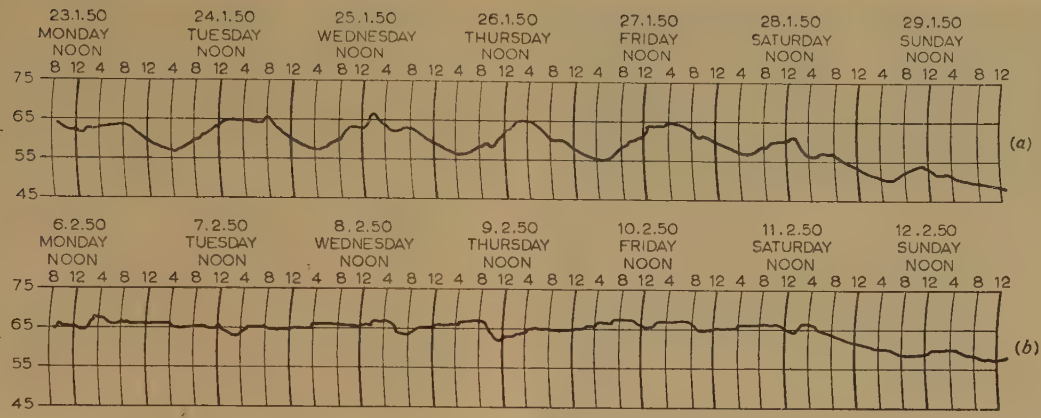

Fig. 3.—Room temperatures with convectors and unit heaters (south room).

(*a*) Two convectors.
(*b*) Three unit heaters.

internal temperature of the south-aspect room, first with convectors (switched in daily at 4 a.m.), which were the previous means of heating the room, and secondly with the storage heaters.

The following main conclusions were drawn from this experiment:

(*a*) There was no need to have the oven-type thermostat as a safety device because, in the event of the control arrangements failing in the closed position such that input of energy was maintained indefinitely, a stable condition would be reached where the output became equal to the input; this would occur when the average surface temperature was about 180° F and was regarded as not being dangerous. Moreover, it was clear that the use of the variable setting of this thermostat as a means of controlling the input of heat placed too much reliance on the user's willingness and memory and was out of keeping with the expressed aim of fully automatic control.

(*b*) Elements contained in tubes that were welded to the case of the heater made too ready a conduction path whereby a proportion of the heat generated by-passed the storage material and resulted in a too-early heating of the outer surface with consequent emission into the room at the beginning of the charging period. It was decided that, in future models, steps must be taken to reduce to ineffective levels any path of good conductivity between the element and the radiating surface—the ideal being an element entirely surrounded by the storage material.

It was, however, apparent that basically the heaters were capable of performing the duty required of them; occupiers of rooms appreciated the blend of radiant and convection heating from the exposed faces (approximately 55% and 45%, respectively) at the time of maximum temperature (see Fig. 4); in particular it was noted that the difference in temperature between the floor level and ceiling was commendably small—of the order of 3° F.

In this early experiment, energy had been available to the heaters for 12 hours during the night and up to 3 hours at midday, although it was recognized that in commercial practice it would be desirable to compress the night charge into about 9 hours and to dispense with any day-time charge. By this means the demand would be restricted to those hours, during the night, when other demand was smallest, and extensive development could occur without overlapping normal day-time demand and perhaps create new 'peaks'; it was felt unwise to rely on the availability of supply at midday, because the relatively shallow valley existing at that time would soon be taken up. Further demand would then be an embarrassment, moreover, owing to the time lag between charging and discharging, and the benefit of a midday 'boost' would often not be apparent until after the end of the working day.

It was considered that, with attention to the matters brought to light in the test and by ensuring an adequate number of heaters

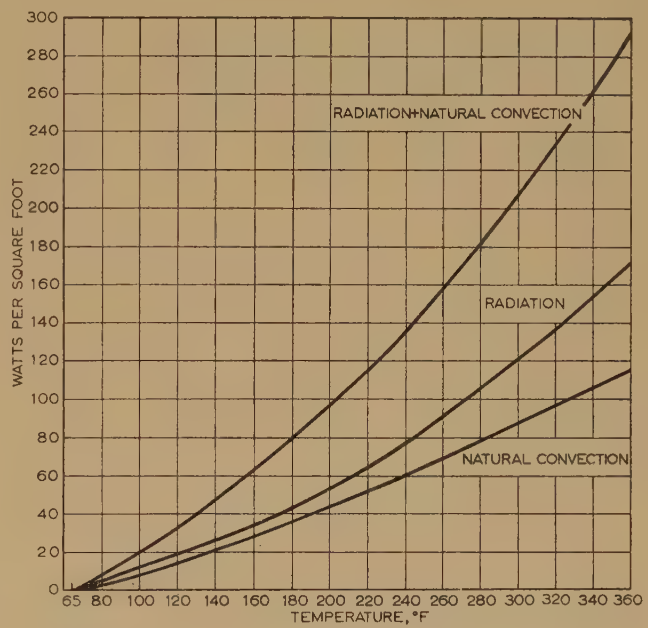

Fig. 4.—Heat transfer from a surface to surroundings at 60° F.

for any particular location, no difficulty would be met in reducing the charging period to the desired level.

It was therefore decided for the winter of 1950–51 to embark on a much larger experimental installation involving some 80 kW of heaters. Experience indicated the desirability of introducing a different heating element, and it was felt that this would best take the form of a flat plate that could be supported either on heat insulators or by metal of so small a cross-section as to reduce conduction to a minimum. It was also considered fundamental that the element should be located centrally in the storage mass, so as to take full advantage of the delayed emission of heat owing to the time taken by the migration of heat through the maximum thickness of storage material.

The result was a decision to use a form of element that had already been developed for soil sterilizing purposes. It consisted of a resistor, mineral-insulated and Inconel-sheathed, the whole being bent to a U-shape and cast into an aluminium plate about ¼ in thick (see Fig. 5).

Because of the advantages of using materials that were readily

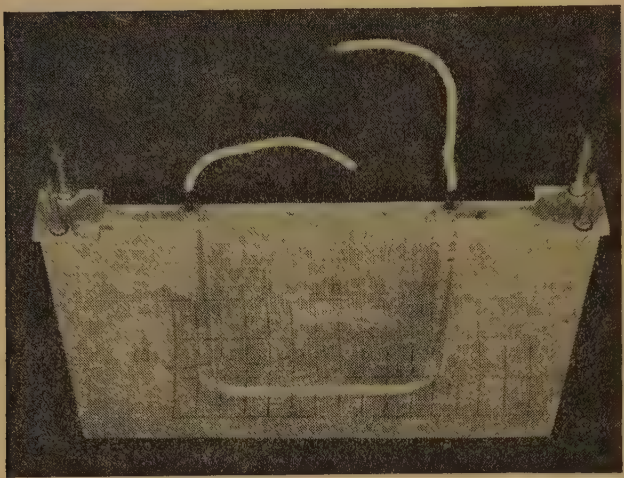

Fig. 5.—Plate-type element.

available, another decision was made to use ordinary fletton bricks instead of the fire bricks previously employed.

Because of the insignificant advantage to be gained at the low temperatures concerned, it was decided not to specify dark finishing colours for the radiating surfaces, and the new heaters were therefore finished in cream to tone with surrounding decorations.

Heat losses were calculated in the conventional manner, and were related to a desire to restrict the charging period to 9 hours nightly (no midday boost) when determining the number of heaters for any room. Location of heaters within rooms was fairly conventional, being mainly beneath windows.

For control purposes the installation was divided into two sections, one including all the rooms on the south side of the building and the other those on the north side. Control was basically by time switches, the operating times of which were adjusted at two-weekly intervals to a programme determined in advance to accord with the advance and decline of the heating season. Additionally, an outdoor thermostat was introduced such that, if the early-morning temperature was appreciably above normal, the heaters would be switched off up to two hours earlier.

In practice, the control was satisfactory in that comfort conditions were maintained in the occupied rooms, but the following drawbacks were noted:

The disadvantage of repeatedly resetting time switches—a task that consumers could not reasonably be expected to undertake.

The influence on switching times of the outdoor thermostat was crude and resulted in concentration of the charge during the earlier part of the night, whereas it should clearly occur as near as possible to the commencement of the occupied period.

It was recognized, of course, that by using a number of time switches and outdoor thermostats with the time settings and temperatures suitably graded, a finer control would result, and indeed this was applied in another installation that was put into service concurrently. Fig. 6 shows the arrangement of time switches and outdoor thermostats that was employed.

However, the aim was to simplify control, to make it fully automatic, to maintain comfort conditions, to achieve economic usage of energy and to do this at a cost which would be commercially attractive. The author sees little value in describing at any greater length these early experiments, but the conclusions resulting from them were manifold, including:

(*a*) An appreciation of the features of transportable thermal-storage heaters that are fundamentally necessary or desirable.

(*b*) An indication of the form of control to be sought.

(*c*) Confirmation that this was a practical method of influencing generation and system load factor.

(*d*) The interest of manufacturers and others had been aroused in this method of heating.

(*e*) The stage had been reached when commercial development might be encouraged.

Later developments on methods of automatic control are described in Section 7, and it is interesting to note that, with its control system brought up to date, the experimental installation just described is still in regular and satisfactory use.

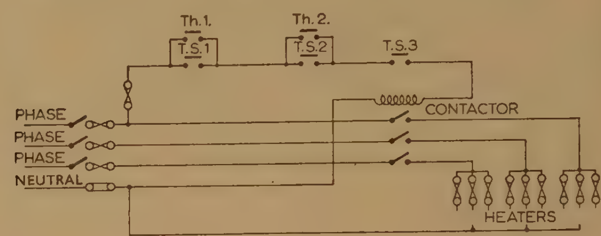

Fig. 6.—Stepped control based on outdoor temperatures.

T.S.1, T.S.2 and T.S.3 are switches of a three-circuit time switch or of three separate time switches.
Th.1 and Th.2 are external thermostats.
Smaller temperature and time steps may be arranged by including additional external thermostats and time-switch circuits. For the arrangement illustrated the suggested instrument settings are as follows:

Time switches			Thermostats	
	In	Out		Setting
T.S.1 T.S.2 T.S.3	4.30 a.m. 1.45 a.m. 11 p.m.	7 a.m. 7 a.m. 7 a.m.	Th.1 Th.2	50° F 40° F

(4) COMMERCIAL DEVELOPMENT OF HEATERS

In a development of this nature the stage is reached where experiments indicate a reasonable possibility of commercial success. It is then necessary and correct that manufacturers, with all their design and productive resources, should take the initiative. The position now, only four years after the experiments just described, is that some four or more manufacturers are producing transportable thermal-storage heaters at a rate of about 20 000 a year.

Although, in principle, they follow the experimental models previously described, there have been improvements along lines that would be expected. By the production of fireclay sections specially moulded, the use of either fire-bricks or building bricks has been mainly discontinued, together with sand to fill interstices. Concrete blocks were experimented with but were abandoned because of drying-out difficulties and a tendency to crack in use.

Heating elements have been simplified and are generally in the form of a resistor wound on a fireclay former, which is part of the storage material.

Sheet-steel cases of pleasing shape and finish have been developed. In the author's experimental heaters a loading of 1 kW was not exceeded, the reason being a desire to avoid all risk of accident due to high surface temperatures (Section 3 shows that, even under fault conditions causing continuous charging, stability was reached at about 180° F, which was considered the maximum safe temperature).

Naturally manufacturers, with a view to the competitive position, sought means by which to increase loadings and storage capacity without a comparable increase in mass. This was simple enough by permitting the storage material to run at much higher temperatures and by restricting the outside surface temperature by interposing a layer of heat insulation (such as

Fibreglass) between the storage blocks and the inner side of the case. Within reasonable limits no objection is seen to this practice, even recognizing the possibility, under conditions of faulty control gear causing continuous charging, of relatively high surface temperatures being reached (these can be as high as 250° F). On the other hand, heaters are offered in which, with a designed 8 hours' charge, surface temperatures of the order of 220–230° F are being attained, and in the author's opinion this introduces an accident risk, especially where children are present. Because the dissipation of heat from the surface relies on its being freely exposed, a fire hazard is created if clothing or other combustible non-heat-conducting materials are inadvertently allowed to cover a heating surface for more than a short time.

This trend towards higher surface temperatures is felt to be a matter calling for careful discipline, because development can suffer serious setbacks if accidents are experienced. The introduction of 'guards' is also felt to be a retrograde step—their mere presence is a suggestion of danger. Moreover, the relative cost of heating installations by transportable thermal-storage heaters and by other comparable means does not require any sacrifice of safety or quality.

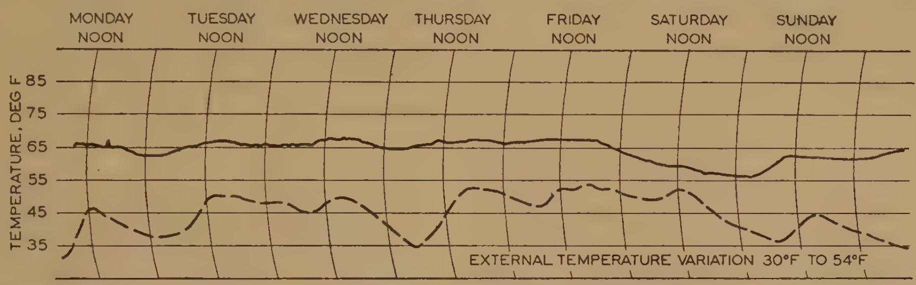

Fig. 7.—Thermograph comparing indoor and outdoor temperatures of a room heated by a thermal-storage unit.

(5) CHOICE OF METHOD OF HEATING

In common with every other form of space heating, thermal-storage heaters are not suitable for every need or situation. For instance, their application is only economic in rooms that are in daily and more or less continuous use. Because of the special characteristics present, more than usual attention needs to be paid to the type of building that is to be heated.

First, the results will be better if the outer walls and roof of the buildings have been insulated to reduce the heat loss through them. But this, on its own, is insufficient; there must be an adequate mass of fabric in the structure because there will be dependence on this mass to store heat during the later part of a charging period and at the beginning of a discharge period, and by its later release to maintain room temperature in spite of a falling output from the heaters themselves.

It is important to remember that it is the partition walls and intermediate floors which in a fully heated building are the most effective to act as storage media, since they are at sensibly the same temperature on both sides.

Unfortunately it appears to be impossible to define positively a relationship between structure and the volume to be heated that could be quoted as a yardstick. But certainly storage heaters should not be recommended for use in a flimsy structure such as sheet steel, sheet asbestos or the like, even if internal insulation has been applied. In buildings of more conventional construction, in order confidently to put forward this method of heating it would normally be necessary to find outside walls not less than 9 in thick, partitions of brick and plaster, intermediate floors of concrete or, if timber, with ceilings of either plaster or ceiling board, only a normal proportion of window area and preferably an insulated roof. Very large rooms, perhaps bounded on all sides by outer walls and having wooden floors below and above, are obviously short of storage capacity; on the other hand, such a deficiency would be made up if the room were, in fact, a workshop accommodating heavy machinery.

Related to the type of construction, some consideration must also be given to the normal hours of occupation. For example, if it were considered that a particular building had the minimum admissible thermal characteristics and it were known that occupation would go on until late every evening, it would be necessary to recognize the possibility of an unacceptable temperature drop in the evening consequent upon the heaters having cooled and the fabric having released too early much of its thermal content. Such a situation might be overcome, of course, if it were possible and economic partly to recharge the heaters at, say, midday.

(6) PLANNING AN INSTALLATION

In practice, the temperature range, throughout each 24 hours, in rooms that are regularly heated by thermal-storage heaters, is relatively small. This is shown by Fig. 7, which is a typical thermograph of a room so heated (outdoor temperatures have been superimposed for comparison).

Nevertheless the approach for planning purposes should be on the basis of intermittent heating (having the benefit of a long pre-heating period), the intention being merely to heat the space during the occupied hours.

The first step is to calculate by conventional methods* the heat loss that will occur during the occupied hours at predetermined design temperatures—usually of the order of 60–65° F internal against 30° F outdoor. Because the control of the equipment will be on input and not on output, it is necessary at this stage to estimate what might be called 'occupational gains' (gains from persons, lighting, machinery, etc.) and to reduce the calculated losses accordingly.

It is considered that no account should be taken of solar gain, because, in closely built commercial areas, winter sunlight is likely to penetrate only a small proportion of upper windows; in isolated premises the solar gain is certainly noticeable, though it is probably offset by the much greater general exposure of the buildings.

It is therefore the net heat losses so derived that have to be met from the heaters to be installed.

Fig. 8 illustrates the heat-output characteristics of a typical 1·5 kW heater when in regular service, and depicts the heat emission in watts during and following the maximum charge of eight hours.

Table 1 sets out the hourly rate of dissipation and indicates that, of the input of 12 kWh, one-third has been emitted during the charging period. This leaves 8 kWh in store in the heater to be released mainly during the occupied period. The Table also shows that, if the occupied hours are from 9 a.m. to 6 p.m., a 1·5 kW heater will, at the commencement of that period, be delivering heat at a rate of 840 watts, that by the end of the

* Institution of Heating and Ventilating Engineers: 'Recommendations for the Computation of Heat Requirements for Buildings.'

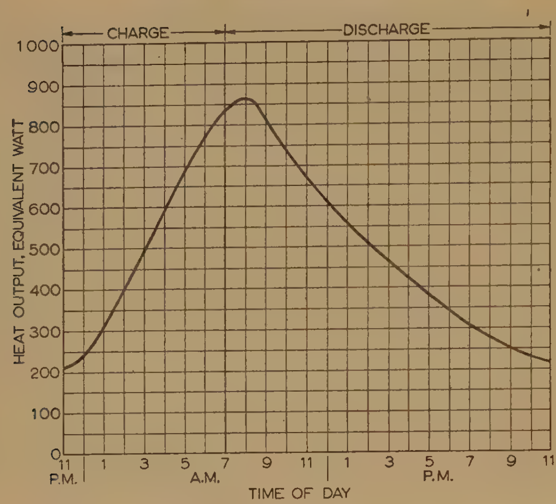

Fig. 8.—Output characteristic of a typical 1·5 kW heater when in regular service.

Table 1

Heat Output from Typical 1·5 kW Heater

Hourly period	In the hourly period	Heat output Total	Total	Remarks
	kWh	kWh		
1st	0·225	0·225		Charge begins
2nd	0·275	0·500		
3rd	0·350	0·850		
4th	0·440	1·290		
5th	0·540	1·830		
6th	0·640	2·470		
7th	0·730	3·200		
8th	0·800	4·000		Charge ends
9th	0·850		0·850	Discharge begins
10th	0·840		1·690	
11th	0·780		2·470	
12th	0·700		3·170	
13th	0·640		3·850	
14th	0·585		4·435	
15th	0·535		4·970	
16th	0·490		5·460	
17th	0·440		5·900	
18th	0·400		6·300	
19th	0·360		6·660	
20th	0·325		6·985	
21st	0·290		7·275	
22nd	0·260		7·535	
23rd	0·240		7·775	
24th	0·220		7·995	Discharge ends
	11·995			

period this will have fallen to 340 watts, and that during the nine-hour period a total of 4·97 kWh will have been supplied to the room. It must be remembered that, during the unoccupied period (doors and windows being closed), almost no air changes will have occurred, the heat loss being restricted almost entirely to that by transmission; also the liberation of heat during that period was rather concentrated into the last 3–4 hours, which might be regarded as the 'preheating' period. At the commencement of the occupied period, therefore, the larger portion of the heat so far liberated will be held in the structural fabric, migrating in the cases of outer walls only towards the colder outer surfaces.

It follows then that, as soon as the output of the heaters has fallen sufficiently to cause a drop in internal air temperature, heat is released from the fabric back into the occupied space. Experience shows that, provided that the building is of the standard construction previously indicated, this release of heat is sufficient to balance the falling output of the heaters completely, or anyway so nearly that the room temperature remains within normally acceptable limits (say $\pm 2\frac{1}{2}$° F) of that designed.

This has been checked for a sufficient number of cases to satisfy the author as to its reliability for design purposes. It means that normally a 1·5 kW heater can be regarded as capable of dealing with a *net* heat loss of approximately 840 watts throughout the occupied period—it appears commonly to be the case that this net heat loss is approximately equivalent to 1 kW loss before deducting 'occupational gains', so that if a rule of thumb were felt to be admissible it would be that, for each 1 kW of calculated heat loss, a 1·5 kW heater should be installed.

In contemplating the use of this method of heating there will be cases of fear either that insufficient structural fabric is present or that the hours of occupation are abnormally long. A rough check can be made by measuring the volumes of different materials surrounding a room; then the theoretical release of heat in British Thermal Units for each degree Fahrenheit fall in room temperature would be found from:

Volume of material in cubic feet × Specific gravity × 62·2 × Specific heat.

In practice, owing to the loss of heat from both sides of walls and of the types of materials and surfaces present, it is necessary that a factor of not more than 0·5 should be applied to the above expression.

The following typical case is given to indicate the application of this check and to support the contentions of Table 1 as to the amount of heating equipment to be installed in a 'normal' case:

Dimensions of office (to accommodate five persons) = 14 ft × 14 ft × 9 ft.

Construction.

Floor: Wood blocks on 6 in concrete (196 ft^2).
Internal walls: $4\frac{1}{2}$ in brick, plastered; net area (14 ft × 9 ft × 2 − (7 ft × 2 ft 6 in) = 235 ft^2.
External walls: $13\frac{1}{2}$ in brick, plastered; net area (14 ft × 9 ft × 2) − (8 ft × 5 ft) = 212 ft^2.
Ceiling: Hardboard of negligible volume.

Calculated heat loss, based on 30–65° F and two air changes per hour = 2·26 kW.

Thus the following volumes of structural material are present:

Floor: 196 ft^2 × 0·5 ft = 98 ft^3 concrete.
Internal walls: 235 ft^2 × 0·5 ft = 117·5 ft^3 bricks and plaster.
External walls: 212 ft^2 × 1·2 ft = 254·5 ft^3 bricks and plaster.
Total bricks and plaster = 372 ft^3.

Taking concrete to have a specific gravity of 2·4 and bricks and plaster 2·0 and the specific heat of both to be 0·2 and applying the formula given earlier, we have:

98 × 2·4 × 62·2 × 0·2 = 2925 B.Th.U. per deg F temperature drop

and 372 × 2·0 × 62·2 × 0·2 = 9 255 B.Th.U. per deg F temperature drop.

12 180 B.Th.U. per deg F temperature drop.

Times the factor 0·5 = 6090 B.Th.U. per deg F temperature drop.

so that the energy released per deg F temperature drop is 1·78 kWh.

The position is summarized as follows:

(a) Calculated heat loss	= 2·26 kW
(b) 'Occupational' gains (five persons)	= 0·5 kW
(c) Proposed number of 1·5 kW heaters to be installed	= 2
(d) Heat required to be supplied by heaters [(a) minus (b)]	= 1·76 kW
(e) Total for nine occupied hours = (d) × 9 ..	= 15·84 kWh
(f) Actual output from heaters = (c) × 4·97 ..	= 9·94 kWh
(g) Deficiency [(e) minus (f)]	= 5·90 kW
(h) Energy from structural thermal capacity per deg F temperature fall	= 1·78 kWh
(i) Therefore temperature drop to be suffered to make good deficiency [(g) divided by (h)] ..	= 3·32° F

This shows a temperature drop which is unlikely to result in discomfort, especially bearing in mind that other 'occupational' gains, e.g. lighting, have been disregarded as also have small temperature variations that result from the tolerances of accuracy of thermostats.

The location of heaters is important for comfort reasons and generally should follow what has become conventional practice with hot-water radiators, special attention being paid to their proximity to cold areas such as windows. Heaters should always stand 3 in from walls or other fabric, and wiring to them should run down the wall not immediately behind them but at least 6 in to either side.

(6.1) Small Installations

The attributes of this method of space heating make it eminently suitable for small commercial or industrial buildings or for small suites of rooms within buildings, such as those occupied by professional people—doctors, accountants and the like. The design of these installations will be in local hands; it will often be considered unnecessary to calculate heat losses, and, without doubt, arbitrary rules will be applied as to the number of heaters required. In the majority of cases the suggestion already made as to a rule-of-thumb method might be further simplified to be that, for each 1 000 ft^3 of air space, a 1·5 kW heater should be fitted, rounding off the loading so derived to the nearest kilowatt above.

In the next Section consideration is given to methods of controlling installations, and it should be borne in mind that over-equipping any installation with heaters is a condition that can be corrected by proper control, but nothing can compensate for too few heaters.

(7) METHODS OF CONTROLLING INSTALLATIONS

(7.1) Large Installations

The first approaches to automatic control were described in Section 3 and were clearly capable of much improvement. The expression 'large installations', in this Section, means installations of ten or more heaters capable of unified control. The number ten is chosen only for economic reasons, because the cost of methods to be recommended would be relatively high for a smaller number.

(7.1.2) Time Control.

All control circuits commence with a time switch, the setting of which will have regard to the maximum charging period for which the heaters are designed and to any time stipulations associated with the tariff for electricity. The charging period should be arranged to end as late on each morning as is permitted by the tariff, probably at about 7 a.m.

Both the accuracy and reliability of the time switch are important—failure with the switch open will result in a cold building; failure with the switch closed might (subject to the operation of thermostatic control) result in overheated equipment and, depending on the tariff, a substantial charge for day-time demand. Consideration should therefore be given to the use of a time switch, which is either escapement-operated electrically wound or synchronous-motor operated with a spring reserve mechanism. Where a building is occupied only five days a week it is necessary for the switch to be fitted with a 'day selector' device; by this means manual control of any sort can be restricted to special occasions such as public holidays when the building might be unoccupied for several days.

Also, sight must not be lost of the reliance, for satisfactory results, that is placed on the reservoir of heat to be held in the building fabric—for this reason it is necessary in buildings that are unoccupied from Friday evening to Monday morning to omit the charge only during Friday night, resuming it as usual on Saturday night. The same principles should be applied over the longer Christmas break, when, in severe weather, it would be wise to resume heating two nights before that ending the day of reoccupation.

(7.1.3) Indoor/Outdoor Thermostatic Control.

A form of thermostatic control that has been used fairly extensively relies on the use of two air thermostats. One is located out of doors, contained in a weatherproof box and exposed as nearly as possible in the same way as the rooms under control (i.e. if it is controlling heaters in rooms having a southerly aspect the thermostat might be placed high up on a south wall, but it should not be close under eaves or in a position that would protect it from rain or other elements to which that face of the building was generally subject).

This thermostat controls, through contactors, the actual heating circuits; it is set normally to close at about 53° F, but its operation is biased in the following manner. Inside the box, in addition to the thermostat, there is a small heating element, of about 12 watts, which is itself controlled by a reverse-acting thermostat fixed in a carefully chosen indoor position and set so that at 65° F (or other predetermined level) its contacts close. The arrangement, shown diagrammatically in Fig. 9, therefore provides that if, upon the time switch closing, the outdoor temperature is below 53° F and the indoor below 65° F, the heaters will be brought in circuit and will remain so until the outdoor thermostat opens. This may be due either to the ambient temperature rising above 53° F or in due course the indoor thermostat closing at 65° F bringing into use the 12-watt element, the effect of which on the outdoor thermostat will

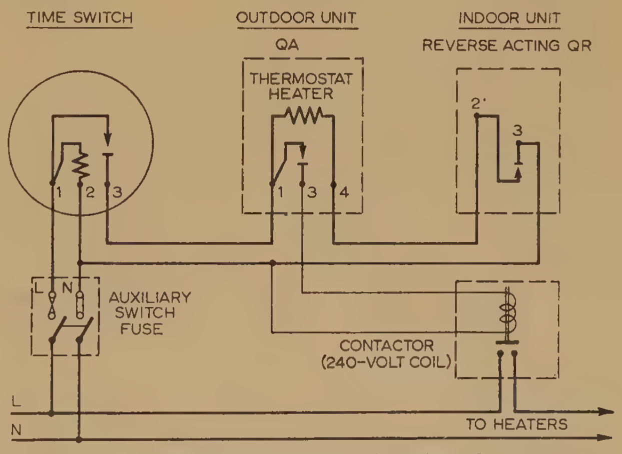

Fig. 9.—Arrangement of indoor and outdoor thermostats.

Normal instrument settings

Time switch: in at 11 p.m. and out at 7 a.m.
QA unit: 53° F to 55° F.
QR unit: 65° F or a little lower.

depend on weather conditions. Dissipation of the heat from the outdoor thermostat box will be affected not only by temperature but by wind and/or rain—elements that will also affect the building heat losses—and in this respect it is advantageous.

Where this method is employed it is desirable to split the installation into sections by orientation, e.g. north and south, in order to achieve the similarity in exposure previously referred to.

Considerable care should be exercised in the choice of the position of the indoor thermostat to ensure that its operating conditions are typical of all the space under control.

A criticism of this method of control lies in the obvious tendency to concentrate the charging period at the beginning of the night, whereas, when conditions warrant less than a full charge, it is desirable for this to take place at the end of the period.

(7.1.4) **Thermo-Time Regulator.**

A typical thermo-time regulator developed for the control of thermal-storage installations consists essentially of a synchronous motor driving a cam which rotates once in 24 hours and the effect of which is to vary, in any predetermined way, the operating setting of a thermostat actuated by outdoor temperature.

A typical cam arrangement is shown in Fig. 10, from which it

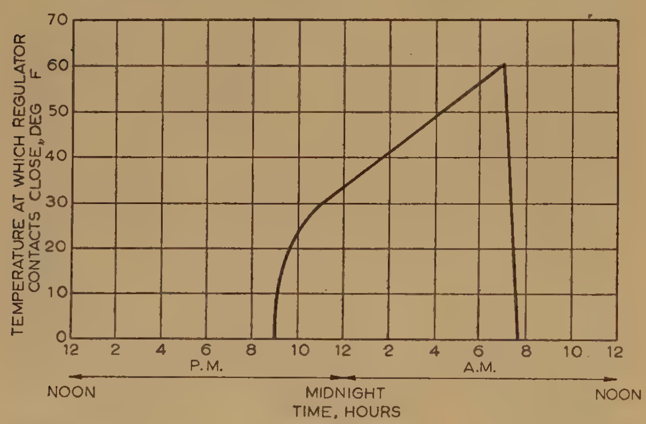

Fig. 10.—Typical cam arrangement on thermo-time regulator.

will be seen that at 11 p.m. the circuit will close if the outdoor temperature is below 30° F, whilst as the night progresses the thermostat setting is raised. Normally this will ensure that the charging period occurs as late as possible. It is sometimes considered advisable to have a short charge, of say 1½ hours, at the end of the period irrespective of actual temperatures, and, of course, a cam could be shaped to achieve this. The object of such an arrangement is to avoid those occasions at the beginning and end of a heating season when no heating is strictly required, but there is some psychological advantage, and complaints will be avoided if staff and/or customers do not arrive in the morning to find cold heaters.

When this type of controller was first made available, some concern was felt at the absence of influence by indoor temperatures, but, in practice, provided that the installation has been properly designed, this influence can be dispensed with, as indoor conditions inevitably follow those outdoors, albeit at some short interval of time. On the other hand, the designer is freed from the need to select a 'typical' indoor site for a thermostat—a matter not always easy.

The thermo-time regulator is available for location out of doors, but the author prefers to fix it indoors with the thermostat actuated through a capillary. Siting of the sensitive bulb needs to be done with care to ensure that it is not unduly screened in any direction.

Observations on the use of thermo-time regulators indicate that there is little value in duplicating the controllers to deal with different solar aspects of building faces—presumably owing to the absence of influence by indoor thermostats which might be located in positions affected by day-time solar gains.

(7.2) Control of Small Installations

Ideally every installation should be controlled by the best means available, but clearly there are economic limits that make it necessary to employ less expensive measures for small installations. In such cases, very acceptable results have been obtained when, in addition to the essential time switch, further control has been simply by room thermostats used where necessary in conjunction with contactors. Experience indicates a tendency by employees occupying rooms to 'meddle' with thermostat settings, and for that reason the use is recommended of thermostats that can be sealed at the proper setting.

(8) USER EXPERIENCE

Since the heaters became available on a commercial basis, the Eastern Electricity Board has installed several thousand in consumers' premises. The majority of installations have been small, i.e. in shops, offices, etc., and often consist of up to about six heaters, though there have been instances where 50 or more have been fitted.

It is gratifying to note that complaints have been extremely few, whilst there have been a number of expressions of satisfaction.

To collect detailed user experience, the Utilization Research Section of the Central Electricity Authority is taking steps to observe certain selected installations with the co-operation of the users and by means of instrumentation. In the meantime it appears that, with installations planned and controlled by the methods indicated in the paper, consumptions of the order of 1 000–1 200 kWh per kilowatt installed per heating season are being experienced, although, unfortunately, information is lacking that would permit this consumption to be compared with the calculated losses during occupied hours in specific installations.

(9) THE FUTURE

The author is convinced that, having regard to the present-day costs of generation, transmission and distribution plant, buildings and equipment, and bearing in mind the spare capacity that exists at every stage at night-time, it is imperative to pursue with vigour the development of storage heating. By thus supplying heat from low-grade coal, oil and later from nuclear energy, much better-grade fuel can be released for important industrial purposes or for export. Moreover, a marked contribution towards a purer atmosphere should result, for it is well known that the inefficient use of coal for space heating is a serious contributor to pollution.

It is therefore considered that all branches of the electrical industry should pay particular attention to the development of this (and other) forms of off-peak usage of energy. Enthusiasm must not, however, overrule discretion, and care must be taken in the choice of buildings, etc., as being suitable for the purpose.

(10) TARIFFS AND DEMANDS

There is probably no incentive more powerful than a financial one, and the availability of a reduced electricity rate for the night-time heating is almost fundamental in this development. The Eastern Electricity Board already offers a reduced night-time rate available to consumers on most of the published tariffs.

Of course, for the larger consumer who purchases energy on a two- or three-part tariff including a demand charge, night-time

energy is bought only at the kilowatt-hour charge—probably well below one penny per kilowatt-hour and about half the average charge for day-time energy. In the event of his night-time demand exceeding that of the day-time, there would appear to be good reason for special consideration.

It is suggested that the electricity supply industry should seek to recover all its fixed costs under the ordinary published 'general purposes' tariffs, so that additional night-time energy, having such desirable characteristics, could be sold at a level just to cover fuel and other production costs, losses (and on relatively unloaded networks these will be lower than average) and a small margin. It is foreseen that, with rising costs of all capital works accompanied by rising generating efficiencies, this differential price advantage is likely to expand until it could become an important factor in encouraging the transfer to night-time of the present substantial and somewhat embarrassing day-time demand caused by heating load.

Unless an attempt is made to divert the day-time heating demand it might well grow to unmanageable dimensions, not only because as a method of heating it is in accord with present-day desires and conditions, but also because the relative cost to the user has never before been so much in favour of electricity.

This is well illustrated by the following comparison* of the estimated average prices of domestic fuels compared with wage levels, taking 1938 as the index equal to 100.

Coal	261
Gas	219
Electricity	110
Wages (building and contracting industry)	307
Wages (all industries)	322

* These figures are derived from the following sources: 'National Income and Expenditure' (H.M. Stationery Office), C.S.O. Annual Abstracts of Statistics.

The figures are provisional and relate to conditions obtaining in 1954; all prices will have risen since then, but the relative position is probably substantially the same.

The comparison relates to *domestic* prices, but is thought to be valuable in indicating a trend, even though at present, owing to the incidence of purchase tax, the field of development for transportable thermal-storage heaters is restricted to commercial and industrial users.

(11) CONCLUSION

The paper has referred to the reasons that prompted a revival of interest in transportable thermal-storage heaters and has described briefly the experimental steps that preceded the production, in this country, of heaters on a commercial basis.

Information on the design and control of installations will have indicated that the method of heating cannot be universally adopted, although it is considered that a wide field for development exists and that it will be to the interest of everybody if this development takes place.

It is considered that substantial progress has been made over a relatively short time but that there should be no relaxation in continued research for improved design.

(12) ACKNOWLEDGMENTS

Acknowledgments are due to the Chairman of the Eastern Electricity Board for permission to prepare and submit the paper. Also to those manufacturers whose goods have been described but whose names do not appear; to those of the author's colleagues who have assisted him in this matter in many ways since its conception; and to the Irish Electricity Supply Board for permission to refer to their experience.

[The discussion on the above paper will be found on page 437.]

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ELECTRICAL FLOOR WARMING

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SUMMARY

The development of off-peak load is of increasing importance to the electricity supply industry, and the paper gives details of experience obtained in developing off-peak electrical floor warming in the south of Scotland. Special features in the design and control of electrical floor warming are discussed, and various methods of installation are described. Particulars are given of some representative installations, including single- and two-storey buildings, multi-storey buildings, and dwelling houses. Actual operating results are quoted and analysed. A section is included on off-peak tariff design, bringing out the South of Scotland Electricity Board's approach to this problem.

Some reference is made to the comparative economics of electrical floor warming and other methods of space heating. In the conclusions it is suggested that, as this method of space heating has so much to commend it, the electricity industry can confidently take further steps in its development. It is also suggested that there is scope for further research in this field.

(1) INTRODUCTION

The high capital investment in electricity generating stations, transmission and distribution systems, in relation to annual revenue from the sale of electricity, has always had the effect of focusing the attention of electricity supply engineers on the improvement of system load factor.

For the combined systems of the Central Electricity Authority and the South of Scotland Electricity Board, the load factor is now some 47%. Recent increases in the capital costs of generation, transmission and distribution plant, together with restrictions on capital expenditure, have emphasized the importance of improvement in load factor, or, in other words, the transfer of load from peak to off-peak periods.

From a generating-plant operating standpoint, the levelling out of load between winter and summer would not be welcomed owing to the necessity to take generating sets, boilers and parts of transmission and distribution systems out of service for annual overhaul. The position which now obtains in most of the country is that very little spare plant is available during the summer months, a point having been reached when the necessary overhaul can only just be fitted into the normal summer reduction in load.

Area Boards are therefore directing particular attention to the improvement in the daily rather than the annual load factor. The need for this, especially during the winter months, is emphasized by the fact that, unless adequate night load is available, modern high-efficiency generating plant either has to operate through the night at uneconomic loadings or be shut down for a few hours during the night, which is also accompanied by loss in thermal efficiency.

A further and important point is the development of the nuclear generating station. The high capital costs of these stations and the expected low running costs, as well as operational considerations, make it highly desirable that they should operate at high load factors.

There is therefore urgent need to develop off-peak applications of electricity, and, if more night-time load is not forthcoming in the near future, artificial off-peak load will have to be created by the construction of pumped water-storage schemes. Already the Central Electricity Authority, the South of Scotland Electricity Board and the North of Scotland Hydro-Electric Board are giving consideration to this, in spite of the disadvantages of high initial cost and substantial pumping losses.

The most economical and satisfactory solution of the load-factor problem is to encourage consumers to increase their demands for electricity during night-time. The greatest possibility appears to lie in the night-time conversion of electricity into some other form of energy which can be stored for a few hours until it is required during the following day, and the most convenient change is from electricity into heat. This is quite a simple conversion, and, using some medium such as water, brick or concrete, the heat can be stored until it is required.

Electrical thermal-storage heating has been in use for many years, and there are at present many successful examples in which an electrode boiler is used, generally in conjunction with a hot-water storage vessel.

More recently, use has been made of the building structure as a heat-storage medium, and this has led to the development of electrical floor warming.

(2) HISTORICAL

The floor warming of buildings is by no means new. It has been reported that the ancient Koreans built a so-called 'spring' room in their dwellings; this was provided with a hollow masonry floor under which fires were burned. Later, the Romans employed a similar method of heating, and Figs. 1 and 2 illustrate the constructional method adopted. Fig. 1 shows a mosaic floor with the furnace arch and stokehold in the foreground. Fig. 2 is a view of the underside of the floor, the furnace opening being in the background. The pillars are 2 ft 6 in high and support slabs

Fig. 1.—Verulamium house, showing mosaic floor, heating ducts and stokehold.

Mr. Moule and Mr. Stevenson are with the South of Scotland Electricity Board.

Fig. 2.—Verulamium house. Underside view of floor showing floor supports and heating ducts.

carrying the floor. Heat was provided by a fire in an external heating chamber, and the hot flue gases were drawn through the passages under the floor into flues built into the walls.

Floor warming in more modern times has taken the form of hot-water pipes embedded in concrete floors of buildings. This was introduced about 1908 and has been fairly extensively developed in America. In order to ensure uniform warmth throughout the building, pipework and control equipment are complicated, and consequently the system is somewhat expensive to install. It does not appear to have been developed to any appreciable extent in this country.

In recent years, rapidly increasing interest has been shown in electrical floor warming in which the hot-water pipes are replaced by electrical-heating cables or wires. Whilst the building is under construction, heating cables or wires are incorporated in the solid concrete floor, thereby enabling the floors to be warmed without the elaboration or expense of hot-water pipes, boiler, boiler house, chimney, etc., generally associated with a hot-water floor-warming system.

One of the earliest examples of electrical floor warming is the heating of air-raid shelters during the Second World War. R. Grierson[1] carried out a considerable amount of investigation into this particular application.

In 1947 the Electrical Research Association published a technical report[2] giving details of laboratory investigations into the characteristics of electrically warmed floors.

The commercial development has been largely carried out in Scotland. J. S. A. Primrose designed a number of electrical floor-heating installations from 1946 onwards in the Glasgow area. These early installations consisted of mains-voltage heating cables laid in solidly-embedded steel conduit. The use of conduit enabled the heating cables to be readily replaced if a fault developed. The conduit was laid on the main structural floor of the building and covered by a screed about 2 in thick. Primrose had the idea of covering the steel conduit with wire netting before the top screed was laid. The wire netting acted as a heat diffuser, taking up a fairly uniform temperature from the conduit and permitting even heat transmission through the screed to the top surface.

In order to increase thermal contact between the conduit and the wire netting, the conduit was replaced by a D-shaped metal housing laid with the flat side uppermost. This flat surface greatly facilitated heat transmission and also permitted the wire netting to be soundly fixed to the metal housing. Later the wire netting was replaced by expanded metal, which gave greater mechanical strength and further improved heat distribution.*

(3) FLOOR WARMING AS A METHOD OF SPACE HEATING

There are important differences between the characteristics of floor warming and of other methods of space heating. Obvious advantages of floor warming are the uniform distribution of warmth throughout the floor area and the 'warm feet with cool head' effect. A critical comparison of space-heating systems involves consideration of physiological and psychological factors, and, before considering details of the electrical form of floor warming, it is necessary to refer to some important space-heating considerations and the special features of heating by warmed floors.

(3.1) Comfort and Air Temperature

It is well known that air temperature by itself may not be a reliable guide to the standard of comfort in a building. Other factors, such as radiation, air velocity and relative humidity, also have important effects. Of these, radiation is particularly significant, since it constitutes the major source of the heat loss from the body. The temperatures of the walls, ceilings and objects in a room can differ quite considerably, with the result that the body radiates more heat to some objects than to others. If all the objects in the room could be brought to some common temperature in such a way that the radiant heat loss of the body remained the same, that would be the 'mean radiant temperature'. This can be calculated or computed graphically from a knowledge of the surface temperatures of objects within a room.

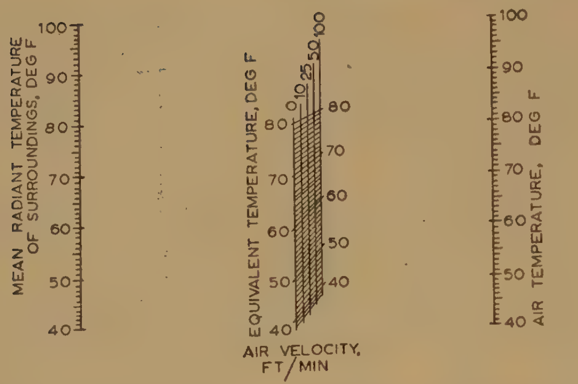
Four factors have therefore to be taken into account in determining the warmth of a room. Attempts have been made to devise a single index to combine these factors, and in this country it is now usual to work to the 'equivalent temperature', which takes into account radiation, air temperature and air velocity, but not the humidity factor. At the space-heating temperatures usually experienced in this country, changes in atmospheric humidity have no great effect and can generally be ignored.

An instrument, known as a eupatheoscope, is available for the direct measurement of equivalent temperature. It consists of a hollow blackened copper cylinder 22 in high and $7\frac{1}{2}$ in diameter, heated by an electrical element to maintain a surface temperature at a value which corresponds to that of the human body. The electrical input required to maintain this (usually 75° F) is a measure of the equivalent temperature.

Dr. Bedford[3] has defined the equivalent temperature of an environment as that temperature of a uniform enclosure in which, in still air, the body would lose heat at the same rate as in the environment.

A convenient method of obtaining equivalent temperature, from a knowledge of air temperature, air velocity and mean radiant temperature, is by the use of Bedford's nomogram, which is reproduced in Fig. 3. From this it will be noted that, with a mean radiant temperature of 70° F and an air temperature of

* This system is the subject of British Patent No. 580709.



[*Crown copyright*

Fig. 3.—Nomogram for estimation of equivalent temperature.
Bedford Industrial Health Research Board Special Report 76.

60° F, the equivalent temperature is 64° F when the air velocity is 10 ft/min.

In circumstances where humidity is an important factor—for instance, where the temperature rises above 70° F—a measurement known as 'effective temperature' is used. This takes into account air temperature, air velocity and humidity, and is thus different from equivalent temperature in that it has regard to humidity but not radiation.

Although the equivalent or effective temperature gives a measure of the warmth of a room, it does not necessarily give a measure of the comfort. This is also affected by the fact that the various parts of the body radiate heat at different rates to the surroundings, by the temperature of the feet as compared with the head, and by other factors which do not affect the total heat loss of the body, but the manner in which it is distributed. Clearly, different persons react to changes of this kind in different ways, and it is difficult to lay down a standard of comfort suitable to everyone.

Much research has been, and is being, carried out, and for further information reference should be made to the papers by Dr. Bedford and others on the subject.[4]

The foregoing brings out several points which are of importance in considering alternative methods of heating:

(*a*) Warmth should be transmitted to the human body mostly by radiation from uniformly warm surroundings.
(*b*) Air movements should be minimized.

The usual convection heating systems are wasteful as well as unsatisfactory. They are wasteful in that the air temperature has to be increased to values higher than would be necessary if the right amount of radiant heat were present. They are unsatisfactory because they lead to excessive air movement and to higher temperatures at ceiling than at floor level.

Practice with floor-heating installations in the south of Scotland suggests that an installation operating with an air temperature of about 61°F at 4 ft 6 in from the floor level provides comfort equivalent to a convection heating system with an air temperature at 65° F at the same height. Fig. 4 gives the results of some early tests carried out by the authors, and the curves show the fundamental difference in the characteristics of the two methods of heating.

(3.2) Heat Flow from Warmed Floors

A warmed floor loses its heat in three ways. Some of the heat given up by the heating system is emitted from the warmed surface of the floor and appears as useful heat in the room. The remainder either disappears downwards into the earth or is transmitted through the edges of the floor into the building structure. A proportion of this last-mentioned loss will warm the inner walls of the building and in turn add to the warmth of the room.

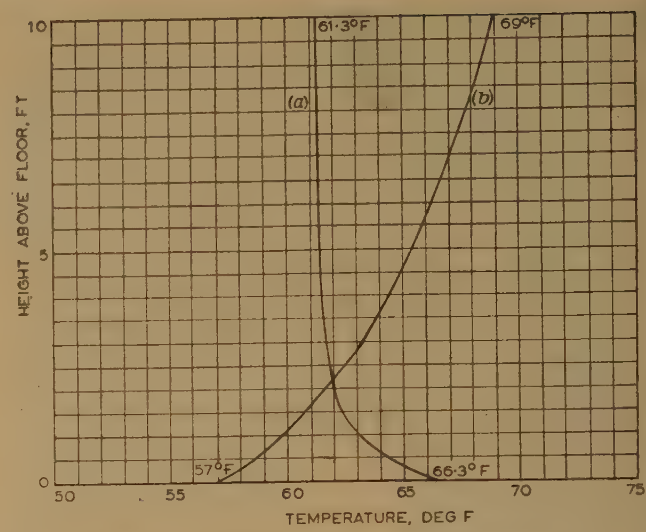


Fig. 4.—Typical room temperature gradients.
(*a*) Electrical floor warming.
(*b*) Convection heating.

The downward and edge head loss of a warmed solid ground floor has been the subject of a fair amount of investigation. Billington[5] has given a detailed account of his studies of the subject using a network analyser. Section 2 of Reference 6 gives particulars of the heat loss both of solid floors and of intermediate floors.

The downward heat loss can be minimized by incorporating a layer of heat-insulating material under the concrete floor, and the edge loss can be substantially reduced by the provision of suitable heat insulation around the edge of the heated floor. Various materials are available for these purposes, and it is usual to employ thicknesses of about one inch.

The heat entering the room from the warmed floor is emitted partly by radiation and partly by convection and can be calculated from the following well-known formulae:

Heat emitted by radiation $= 0\cdot173\,\epsilon\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4$ British thermal units per hour per square foot;

Heat emitted by convection $= C(T_1 - T_2)^{5/4}$ British thermal units per hour per square foot;

where ϵ is the emissivity of floor surface;
where T_1 = Temperature of floor surface, absolute deg F.
T_2 = Temperature of surrounding air, absolute deg F.
C = Coefficient of free convection, which for a warmed floor is about 0·40.

Fig. 5 gives the results of some tests carried out, with the assistance of the C.E.A. Research Department, on an electrically-floor-heated building in Scotland. It shows the way in which the radiation and convection heat emission varied during the heating-up period of a concrete floor.

(3.3) Floor Surface Temperatures

One of the most critical features about floor-warming installations is the surface temperature of the floor. Two conflicting considerations are the need for a high temperature to emit the

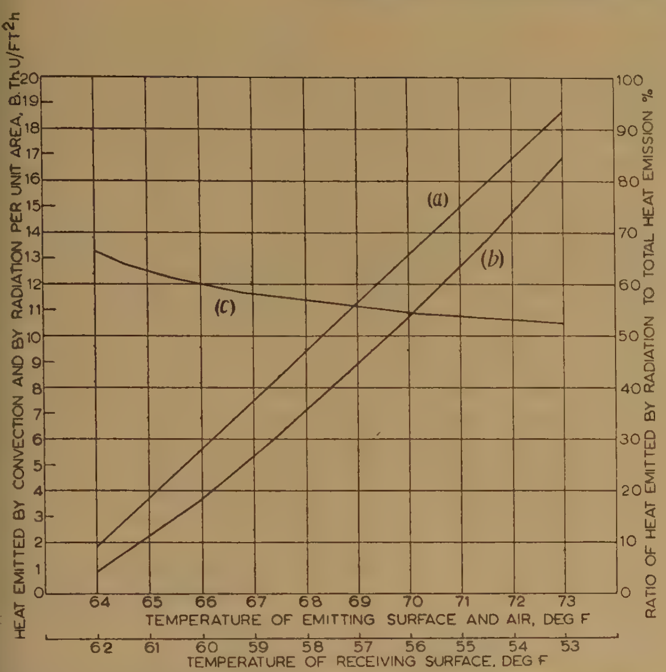


Fig. 5.—Variation in mode of heat transfer during heating-up period.

(*a*) Heat emitted by radiation.
(*b*) Heat emitted by convection.
(*c*) Heat emitted by radiation divided by total heat emitted.

required amount of heat into the room and the fact that too high a surface temperature will cause discomfort to the feet. Bedford[4] gives particulars of observations made in schools warmed by means of heated floors, and his conclusion is that they are satisfactory as long as the temperature of the floor surface does not exceed 75° F.

Adlam,[7] writing of practice in North America, refers to a maximum average floor temperature of 85° F, and apparently this is a basis commonly adopted there. It should be noted, however, that as 85° F is a maximum surface temperature during extremely cold weather, the average temperature would be substantially lower.

Electrical floor-warming installations in the south of Scotland are designed for a maximum floor surface temperature of 73° F. It is found that, apart from a few exceptional cases, a floor surface temperature of that order will provide the needed warmth during severe wintry weather.

Extensive inquiries have been made among occupants of floor-heated premises, and it appears that a surface temperature of 73° F does not cause discomfort to the feet. On the contrary, a warmed floor during very cold weather has proved to be one of the most acceptable features of such a building.

(3.4) Floor Coverings

Where the floor of a building is made of concrete, some form of covering is generally provided. With an unheated concrete floor, the covering is necessary to prevent heat loss and a resultant cold floor, but floor coverings are also often used in floor-heated buildings, partly for appearance and partly for comfort.

The covering of a warmed floor acts as a barrier to the emission of heat into the room. The temperature of the floor builds up, however, until the surface temperature of the covering is the same as the former surface temperature of the bare concrete floor. Although the total heat input into the room remains unaffected by the presence of a covering, the general temperature of the concrete floor is increased, and as a result the downwards and edge heat losses go up. Tests carried out with ordinary-quality carpets and $\frac{3}{8}$ in hardwood floors indicate that the surface temperatures of the concrete may be increased by as much as 10° F and the total heat input by 3–5%.

Apart from the question of the surface temperature, the emission of heat from a covered floor is affected by the emissivity of the material used in the covering. For instance, rough concrete has an emissivity of 0·95, whereas polished wood has an emissivity of 0·91. Linoleum may be as low as 0·90.

In one of the South of Scotland Electricity Board's premises, trials have taken place with 13 different floor coverings, including rubber, cork, wood, various proprietary thermoplastic floor coverings and linoleum. In no case has the application of these floor coverings revealed any marked difference in the heating of the premises. In other premises, floor-heated rooms have been equipped with fitted carpets, and tests have shown that there is no appreciable loss of heat emission from the floor.

During five years' experience in the use of floor coverings on heated floors, no adverse effect on the coverings has been noticed. An interesting fact that has emerged from laboratory tests on a sample of rubber flooring after four years' use is that its actual wearing qualities are better rather than worse when used on a warmed floor. The figures supplied to the authors by the company concerned are as follows:

	New material	Material fitted on an electrically heated floor approximately four years old	Material fitted on a cold floor approximately four years old
Breaking load	1 079 lb/in²	724 lb/in²	731 lb/in²
Percentage elongation at break	365%	225%	190%
Hardness (British Standard degrees)	72	80	77
Compression set (under constant load	4·4%	6·2%	6·5%
Abrasion loss	16·3 cm³/h	12·7 cm³/h	11·3 cm³/h

An interpretation of these results may be summarized as follows. The percentage breaking load is better after use on a cold floor, but when the materials are laid in position, the breaking load and elongation are not, in fact, of much significance. It is, however, desirable that the aged material be harder. From the results of the compression tests and abrasion loss, it can be seen that the material used on the warmed floor is better.

Manufacturers of floor coverings are generally quite confident about their products being used on electrically heated floors, provided that the surface temperature does not exceed 73° F. The temperature of the under-surface of the carpet, wood or other covering may, of course, be up to 10° F higher than this. Wood, when used as a covering on a warmed floor, should be dried to an 8% moisture content; otherwise, after being in service for a short time, it will dry and contract. No difficulty has been experienced with wood-floor coverings where this precaution has been taken.

(4) DESIGN

(4.1) Building Heat Loss

The design of a heating system for a building requires knowledge of the thermal properties of the structure enclosing the space to be heated. It is usual to calculate the output of the heating system having regard to the rate of heat flow through the enclosing structure under steady-state conditions at certain given external and internal temperatures.

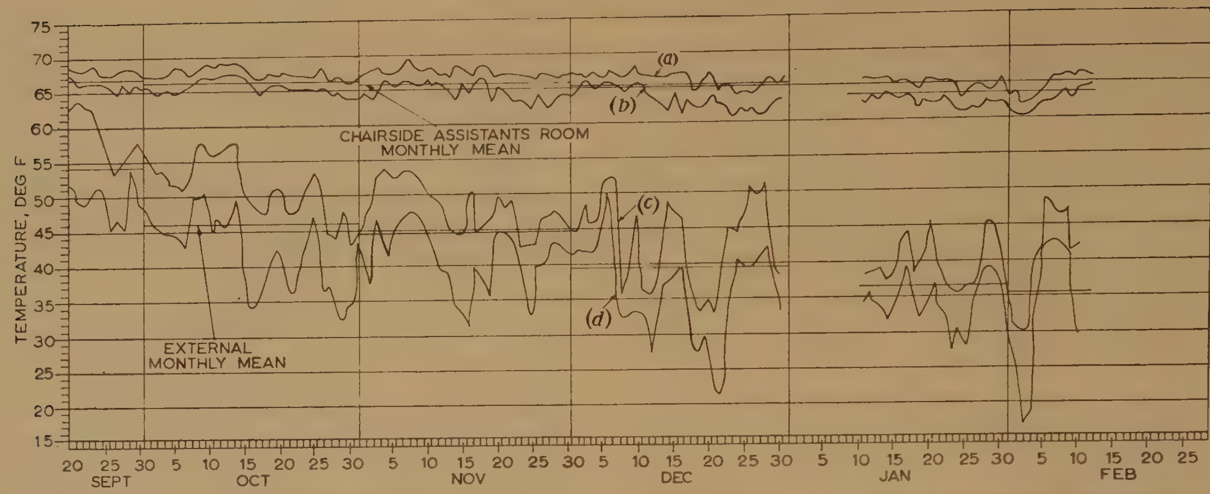


Fig. 6.—The Health Centre, Sighthill, Edinburgh. Floor heating 1955–56. Daily maximum and minimum air temperatures.
(*a*) Maximum daily room air temperature.
(*b*) Minimum daily room air temperature.
(*c*) Maximum daily external air temperature.
(*d*) Minimum daily external air temperature.

Various types of building structure differ widely in their resistance to heat transmission, and to calculate the heat loss of a building, it is necessary to ascertain the thermal transmittance or *U*-value, which is defined as the number of British thermal units transmitted through 1 ft^2 of the building per hour for 1° F difference of air temperature on either side. The *U*-values for various types of structure can be obtained from Reference 6.

It may be noted that a solid 9 in brick wall without plaster has a *U*-value varying from 0·39 to 0·53, depending upon the orientation of the building and its exposure to wind, whereas an unventilated cavity brick wall with glass fibre in the cavity has a *U*-value below 0·1. Single windows of glass usually have a *U*-value as high as 1·0, but double glazing can reduce this to less than 0·5. Good heat insulation is highly desirable for all heated buildings, and it is specially important for floor-heated ones. The figures given indicate the substantial economies made possible by providing a building with good thermal insulation.

To assess the heat loss of a building, it is necessary to calculate the heat loss of each individual room, corridor and other internal space, and this can be done from a consideration of the surface area of the walls, floors and ceilings, and the *U*-value of the materials which compose them. In addition to the loss of heat through the structure, a heated building also loses warmth owing to ventilation of the internal space. For certain types of building, e.g. schools, industrial premises, etc., standards are laid down by the authorities of the number of air changes required each hour. The heat lost through changing the air is readily calculated by multiplying the volume of air displaced every hour by 0·02, the specific heat of air.

For heating systems other than floor heating, a further allowance is usually made for the height of the building. This takes the form of an overall percentage addition to the sum of the structure and the air-change heat losses.

(4.2) Electrical Loading

The ascertainment of the electrical load of a floor-warming installation is determined by reference to the building heat loss and to a given minimum external air temperature. This temperature need not be as low as the minimum temperature actually recorded in the neighbourhood of the building, as account can be taken of the building's ability to store heat. Sufficient heat is normally stored in the building structure to meet the additional heat losses during a severe but short cold period.

As the building is to be heated with a restricted electricity supply, the electrical loading must be sufficient to permit the energy input during off-peak periods to meet the heat loss throughout the 24 hours.

Fig. 6 shows that, during cold weather in February, 1956, a minimum temperature of 16·2° F was recorded at the Sighthill Health Centre, Edinburgh. The mean temperature on the same day was 22·6° F, and throughout the week 34·5° F. The disconnection of the supply, in accordance with the off-peak tariff conditions, does not result in appreciable variations in internal temperature. The effects of solar heat and occupancy heat gained during the day are that temperatures are normally well maintained or even increased during the mornings, while in the afternoons the drop in temperature amounts to only one or two deg F. During the coldest day in the 1955–56 heating season, the maximum decrease in internal air temperatures recorded at Sighthill Health Centre, during the period of disconnection of the electricity supply, was 2·6° F.

In most localities in the south of Scotland, floor-warming installations can safely be designed against a minimum outside temperature of 28° F, although, in a few special circumstances, it has been necessary to work to a much lower figure. A case in point is an installation near Innerleithen, Peeblesshire. Low-lying areas surrounded by hills can be much colder than more open situations, especially on still, cloudless, winter nights, and intense cold can be recorded in these 'basins'. Innerleithen is in this position, and, in order to overcome the extreme cold (as low as −4° F) sometimes experienced in this area, the floor-warming installation was designed to provide normal comfort against an outside temperature of 20° F. This emphasizes the necessity of investigating local circumstances in designing space-heating installations.

Quite apart from outside temperatures, windage can have an important effect on building heating. This factor is well known and taken into account in conventional heating calculations.

As already mentioned in Section 3.3, the surface temperature of the floor should not exceed 73° F, and, where the required power loading cannot be accommodated in the floor without exceeding that temperature, the floor warming can be supplemented by low-temperature radiant-heating panels installed in the walls. This was, in fact, done in the Innerleithen installation.

(4.3) Seasonal Electricity Consumption

One of the most difficult calculations associated with a heating system is the accurate estimation of the consumption of fuel.

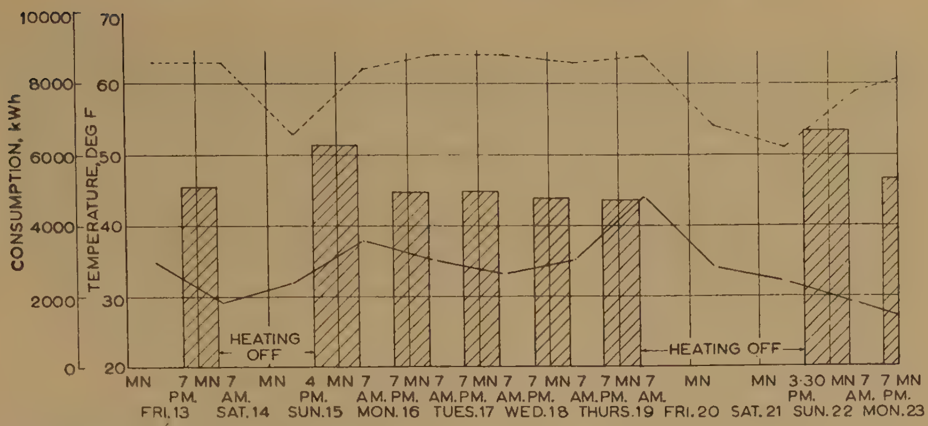


Fig. 7.—St. Mungo's Roman Catholic School, Falkirk. Typical class-room temperatures during January, 1956.

— — — Inside air temperature at 9 a.m.
——— Outside air temperature at 9 a.m.
Daily electricity consumption.

Several methods are available, and they can give results sufficiently accurate for practical purposes. Unforeseen sources of variation arise, however, particularly with new buildings, where many variables have to be taken into account, including, quite often, changes in building construction during erection.

Methods of calculating seasonal fuel consumption are generally based upon either the calculated heat loss or 'degree-days'.

Using the heat-loss method, the estimated electricity consumption for the heating period can be obtained from the expression

$$\frac{H(T_1 - T_2)t}{(T_3 - T_4)3\,412}$$

where H = Calculated heat loss (see Section 4.1).
t = Heating period, hours.
T_1 = Average internal temperature throughout heating period, deg F.
T_2 = Average external temperature throughout heating period, deg F.
T_3 = Internal design temperature, deg F.
T_4 = External design temperature, deg F.

The average external temperatures for various parts of Great Britain are given in Reference 8. Conditions can vary considerably in a short distance, and in hilly districts, in particular, local information is essential if a reliable estimate is to be made.

The degree-day method of estimating electricity consumption is based upon the fact that, if other conditions remain constant, the heat required in a building is proportional to the difference between the internal and external temperatures. The degree-days are obtained from the differences between the heating standard, say 60° F, and the daily mean external temperatures taken for each day during the period under consideration.

The estimated electricity consumption is arrived at by multiplying the degree-days over the heating season by the hourly heat loss of the building and dividing by 3412.

(4.4) Control

Often a person's first reaction to electrical floor warming is that it is inflexible and difficult to control. Fears may be expressed that, if an unexpectedly mild day should occur during the heating season, temperatures would rise within the building and cause discomfort. In practice, however, it is found that the warm floor is to a certain extent self-regulating, as its temperature should never exceed 73° F. If internal temperatures rise owing to mild weather, the rate of heat emission from the floor is automatically reduced. Similarly if an extremely cold period should occur, the floor will immediately emit heat at an increased rate.

During a warm day the floor gives up comparatively little heat, and a correspondingly small electricity input is taken during the following night. This is illustrated in Fig. 7, which will be described later.

Floor thermostats maintain the temperature of a floor at a predetermined value. They do not take into account temperature conditions in the heated room, but they are a useful means of control in buildings, such as garages, where there is excessive air movement.

Air thermostats have been used extensively to control floor-warming installations, and a type is available with a semi-spherical cover, which, it is claimed, responds to a radiant rather than an air temperature. An air thermostat will adjust the electricity input to the floor during the electricity intake period to give conditions in the room corresponding to the thermostat setting. When the electricity supply is interrupted, the thermostat becomes ineffective and the floor very gradually falls in temperature.

To avoid unnecessary heating of the floor during mild weather, automatic regulators have been recently introduced. These instruments work in conjunction with an outside thermostat, and delay the switching on of the electricity supply as long as possible.

Fig. 8 shows the arrangement of one make of regulator and a typical cam profile. The instrument is usually mounted on an outside north wall of the building. Both the cam, and a bi-metal strip reflecting the outside temperature, operate on a lever system which opens and closes a switch. This is in series with the time switch controlling the floor-heating supply. Individual air thermostats adjust the warmth of each room or group of rooms to the desired comfort level.

To prevent undue depletion of the heat stored in the floor, the cam of the regulator is designed to provide a minimum of four hours' electricity input each night.

The manufacturer of this particular regulator now has available another type in which the bi-metal strip is replaced by a large-bore capillary tube about 8 ft in length. Part of the tube is installed within the building and part is left outside. If internal and external temperatures are low, the switching in of the floor-heating supply takes place early, but if the internal and/or external temperatures are higher, the switching is suitably delayed.

A second type of regulator consists of an externally mounted controller which contains an air thermostat, the setting of which

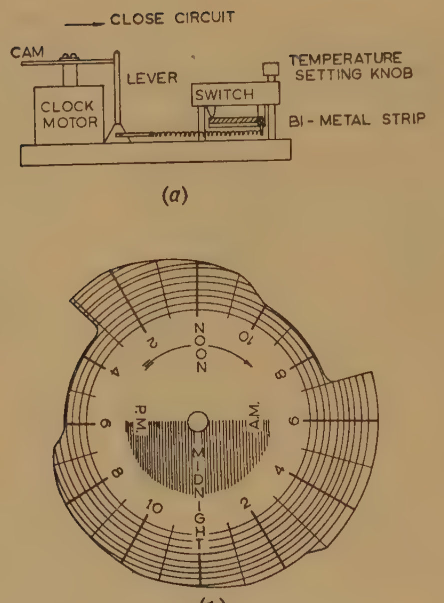


Fig. 8.—Thermo-time regulator.
(*a*) General arrangement of regulator with bi-metallic strip.
(*b*) Typical cam arrangement.

is slowly swept over a range of 25° F during the operating period by a cam driven from a small synchronous motor. The operation of the time switch controlling the supply starts the cam drive with the thermostat at its low setting. The electrical floor-warming equipment is not switched on until the thermostat setting reaches the ambient temperature. After the time switch opens and cuts off the floor-warming supply, the cam continues to rotate and switches off its small drive motor at the end of the day ready to start another cycle when the time-switch contacts close again. The supply to the floor-warming installation under this system is always provided at the latest time permitted under the off-peak tariff.

Experience with these regulators has proved that they are most effective in securing a minimum electricity consumption for this type of building heating. Steps should, however, be taken to prevent the heat stored in the floor being inadvertently reduced to a value which would be inadequate to meet an unexpectedly prolonged cold spell.

(5) SOME INSTALLATIONS IN THE SOUTH OF SCOTLAND

(5.1) Types of Electrical Floor Warming

Electrical floor-warming installations can be classified into two main categories:

Types in which a heating cable or wire is buried solidly in the concrete floor.

Types in which circular or D-shaped metal housings are incorporated in the concrete floor in such a way that, after completion of the building, heating cables can be readily drawn into them.

(5.1.1) Solidly-Embedded Systems.

The solidly-embedded type of floor-warming installation is cheaper to install, but suffers from the disadvantage that the concrete screed has to be broken up should it be necessary to renew or repair a faulty heating cable.

Although at first there was considerable hesitancy about the adoption of solidly-embedded cable, a number of these installations have been carried out, particularly for private dwelling houses. Low initial cost is generally the deciding factor. The heating cables and wires used include the following:

(*a*) Insulated or bare wire supplied from transformers.
(*b*) Mains-voltage cables finished either with a p.v.c. or a metal sheathing.

The p.v.c.-covered cable possesses the advantage of being chemically inert should there be a likelihood of corrosive substances in or around the concrete floor. To permit uniform heating with screeds of $1\frac{1}{2}$ or 2 in it is desirable that the heating cables be laid no more than 3 in apart. If the floor-heating installation has a loading of 10 watts/ft^2, the maximum cable loading will be $2\frac{1}{2}$ watts per foot run.

One type of p.v.c.-insulated cable is supplied complete with copper tails of any desired length, which simplifies and cheapens installation work.

Recent development in fault-localizing equipment has resulted in the production of an instrument which successfully pin-points an open-circuit. It enables a fault to be opened up and repaired with little disturbance to the concrete floor.

Fig. 9 shows a transformer-operated floor-warming installation in the course of installation. The heating cable is a 7/0·052 in p.v.c.-covered copper wire, 160 yd in length. The cable is supplied from a 3 kVA 240/25-volt transformer, which can be seen to the right of the Figure. The heating cable was laid with the assistance of temporary wooden guides at the ends and at intervals along the run of the cable. An end and an intermediate guide can be seen. Part of the concrete screed has been laid.

This installation was carried out in one of the Board's buildings as an experiment. Transformer-operated floor warming has the disadvantages of a higher capital cost than a solidly-embedded mains-operated heating cable, the risk of objectionable noise from the transformer, and the difficulty in accommodating it, especially in dwelling houses. The main advantage is the robust nature of the cable compared with the much finer wire used in a mains-operated cable.

Fig. 9 is a typical example of the layout of a solidly-embedded cable system.

(5.1.2) Withdrawable Systems.

Two manufacturers produce floor-heating systems of the withdrawable type. One operates the British Patent referred to in Section 2, and the system is in extensive use. It consists of D-shaped metal housings placed in parallel lines across the structural floor of a building, the flat side of the housing being uppermost. Housings are generally between 6 and 12 in apart, the precise distance being determined by the electrical loading. They terminate in troughs at the two opposite ends of the room, the height of the troughs being such that, when the covers are in position, they will be flush with the floor surface. In small buildings, such as dwelling houses, only one trough may be necessary, the remote ends of the housings being connected by a semicircular bend of steel conduit. The trough serves to give permanent access to the housings to permit the heating cable to be installed, and to carry the electrical wiring and connections to the heating cables. Expanded metal is laid across the housings and secured to the flat side. A concrete screed about 2 in deep is laid to give the final floor surface. Fig. 10 shows a typical installation of this type in course of construction. Wood shuttering used in the formation of the cable trough is seen in the foreground. The housings, which will later accommodate the heating cables, run from the trough to the opposite end of the room where the expanded metal heat diffuser has been placed in position. The trough can be fixed on a wall a foot or so above the floor instead of in the floor. This is particularly advantageous when the floor is liable to flooding, e.g. with

Fig. 9.—Typical arrangement of a solidly-embedded floor-warming installation.

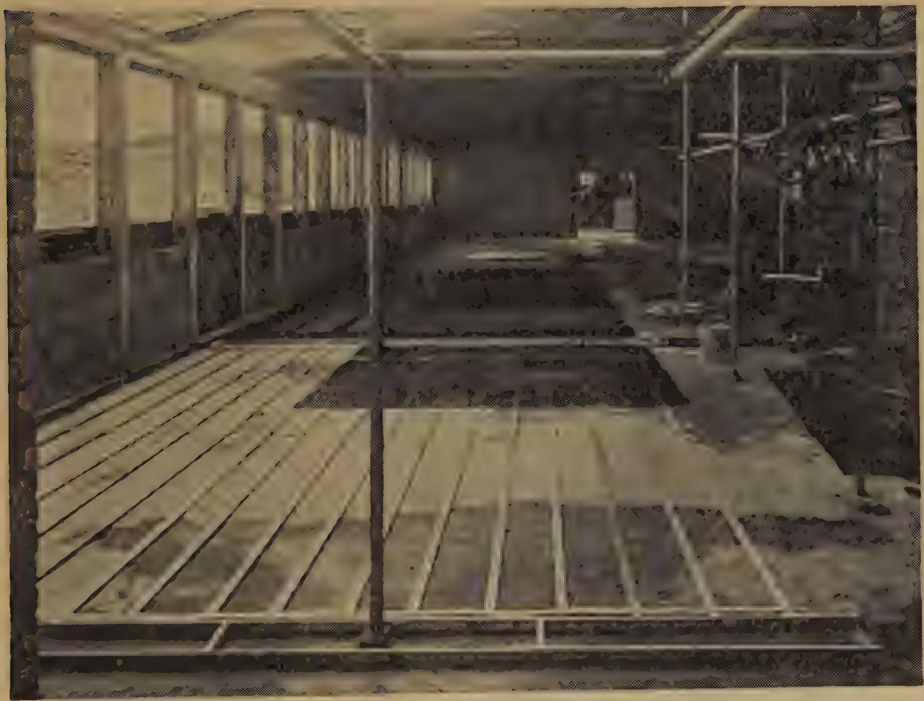


Fig. 10.—Withdrawable type of electrical floor warming in course of installation.

garages. When troughs are mounted on the wall, bent conduit takes the heating cable from the housing into the trough.

Fig. 11 is a typical layout for this type of floor warming as used in a dwelling house. The sectional views illustrate the method of installation.

The second system of withdrawable floor warming comprises round metal conduit installed in the floor in much the same way as in the first system. It suffers from the disadvantage that a heat diffuser cannot be used.

(5.2) Particulars of Some Actual Installations

Many successful electrical floor-heating installations have been installed in the south of Scotland, and examples are given in Table 1. It is convenient to classify them in the following manner:

Large single- and two-storey buildings.
Multi-storey buildings.
Dwelling houses.

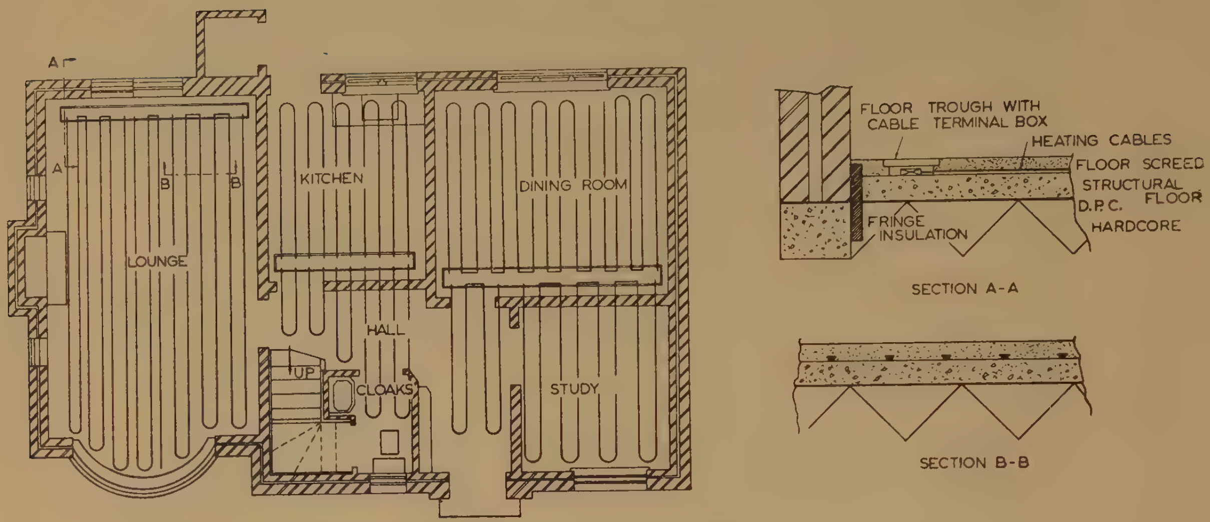


Fig. 11.—Electrical floor-warming layout for a private dwelling house.

Typical layout of heating cables and cross-sections of a solid floor.

Table 1

PARTICULARS OF SOME OF THE LARGER ELECTRICAL FLOOR-WARMING INSTALLATIONS IN THE SOUTH OF SCOTLAND

Reference	Type of building	Size of building		Building heat loss	Heating installation		Estimated annual consumption	Average temperature rise	Capital cost of floor-warming installation	Estimated operating cost
		Floor area	Volume		Loading in floors	Loading in walls and ceilings				
		ft²	ft³	B.Th.U./h	kW	kW	kWh	°F	£	£
A	Industrial	24 000	365 000	975 060	284·07	2·25	406 000	32	5 170	1 070
B	School	42 200	496 425	1 300 000	389·77		650 000	30	11 550	2 750
C	Public services	30 500	258 000	870 000	232	30	393 000	35	9 645	1 500
D	School	24 120	265 000	662 190	215	3·35	337 500	27	8 812†	1 810†
E	School (stage 1)	15 870	164 950	760 850	200	30	381 600	42	8 180	1 720
F	Public services (stage 1)	9 405	96 680	304 110	78·58	22·08	180 000	32	13 420*	3 540
G	Fire station	6 276	61 500	238 000	68·25	0·75	110 000	32	1 910	458
H	School	Approx. 84 900	910 000	2 750 000	860	—	1 290 000	35	23 500	3 760
I	Industrial	8 880	71 040	266 400	110	—	127 000	32	1 207	370
J	Industrial	Approx. 83 000	788 500	3 000 000	880	—	1 320 000	32	24 550	3 850
K	Domestic	14 980‡	132 240‡	560 000	164	—	256 000	32	4 210	800
L	Domestic	10 630‡	79 740‡	510 000	148	—	250 000	32	3 950	780

* Costs for a total installation of 650 kW.
† Costs include domestic hot-water supplies.
‡ Living room and hall only.

(5.2.1) Large Single- and Two-Storey Buildings.

Electrical floor warming first came into its own in large single- and two-storey buildings. These are almost always provided with concrete floors, and building design is therefore hardly affected by the inclusion of a floor-warming system. In fact, considerable simplification is possible owing to the elimination of boiler house and chimney, and the provision of heating pipes, radiators, etc.

Edinburgh Health Centre.—The first large building to be provided with electrical floor warming, after nationalization of the supply industry, was the Sighthill Health Centre, Edinburgh. This building has been fully described in Reference 9.

Brief technical particulars are given in C of Table 1. The building was completed during the winter of 1952–53, and the consumption of electricity for space heating during the heating seasons since that date has been as follows:

	kWh
1953–54	372 649
1954–55	398 992
1955–56	453 217

This building was not fully occupied during the winter of 1953–54; otherwise the floor-warming electricity consumption would probably have been higher than the estimate of 393 000 kWh. This was expected, since new buildings generally consume rather more heat during the first heating season owing to the evaporation of moisture in the drying-out process.

The electricity consumption during the heating season of 1954–55 was extremely close to the original estimate. During

1955–56 some experiments were carried out with an automatic regulator, but unfortunately these were complicated by the provision of additional warmth in the medical sections of the building and the connection of the electrical water-heating system to the off-peak circuit. A satisfactory method of automatic operation has been evolved, and it is anticipated that, in future, the floor-heating electricity consumption will again be within the original estimate.

St. Mungo's School (Stirlingshire County Council), Falkirk.—This building is referred to in B of Table 1, and, as details have not so far been published, it is felt that brief particulars should be given.

St. Mungo's is a mixed school, ultimately designed to take 500 children with a staff of 25, and is fully equipped for art, domestic science, woodwork, metalwork and other technical subjects. The building so far erected, which caters for 300 children with a staff of 16, was completed and occupied in September, 1953. It comprises all the technical classrooms and laboratories, a few general classrooms, a gymnasium, and a large dining hall and kitchen. The whole school will be heated by the withdrawable type of electrical floor warming, which incorporates an expanded metal heat diffuser. The first section has a loading of 390 kW. Each classroom has separate radiant-dome thermostats.

One of the special features of the building is the gymnasium floor. As some resilience was required, the concrete floor was overlaid with 2 in × 2 in battens, spaced 18 in apart. Between these battens the floor-warming equipment was installed and the space filled with dry sand. The floor was finally finished in hardwood strip.

The electrical floor-warming consumption during the three heating seasons was as follows:

	kWh
1953–54	823 010
1954–55	725 980
1955–56	630 450

As expected, the consumption during the first heating season was appreciably above the estimate, but it is encouraging to note that, since that winter, the electrical floor-warming consumption has progressively decreased. The great improvement shown for 1955–56 is in large measure due to the manual operation of the floor-heating main switch to a planned programme, prior to the installation of an automatic regulator.

It is of interest that the sickness rate at this school has been extremely low.

(5.2.2) Multi-Storey Buildings.

Fife County Council Offices.—Probably the first important multi-storey building to be equipped with electrical floor warming was the Cupar offices of the Fife County Council, which is referred to as F in Table 1. The building is partly four and partly five storeys high, and is being constructed in five stages; the first was completed in 1954 and the second in January, 1956. The electrical floor-warming loadings are 79 kW in the first section of the building and 125 kW in the second. The first section also contains 22 kW of wall heating.

Unfortunately, records of electricity consumption are complicated because, during the first heating season of 1954–55, the first section of the building was not fully occupied. The actual electricity consumption was 139 950 kWh, compared with an estimate of 180 000 kWh. During the last heating season the electricity consumption up to the end of 1955 showed a decrease on the estimate. In January, the second section of the building was heated and the floor-warming consumption for the heating season amounted to 213 170 kWh.

Kirkcaldy Multi-storey Flats.—The floor-warmed Kirkcaldy multi-storey flats have already been fully described by one of the authors.[10] Briefly, they have been built without fireplaces and flues, and no gas supplies are available. The building is eight storeys high and contains 24 two-apartment flats and 24 three-apartment flats. Electrical floor warming is installed in the main living room and hall of each flat. The floor warming and a 3 kW electric water heater are supplied under an off-peak tariff. A 2 kW 'coal effect' fire has been provided to afford a focal point for each living room and to give supplementary heating during very cold weather. It is connected to the normal supply which is also used for cooking, lighting, etc. The floor-warming loadings are as folllows:

	Two-apartment flat	*Three-apartment flat*
Ground floor	3 kW	4·1 kW
Each intermediate floor	2·6 kW	3 kW
Top floor	3·75 kW	4·85 kW

The flats were fully tenanted from 1st July, 1955. Details of the electricity normal supply and off-peak supply consumptions for the two- and three-apartment flats are given in Fig. 12.

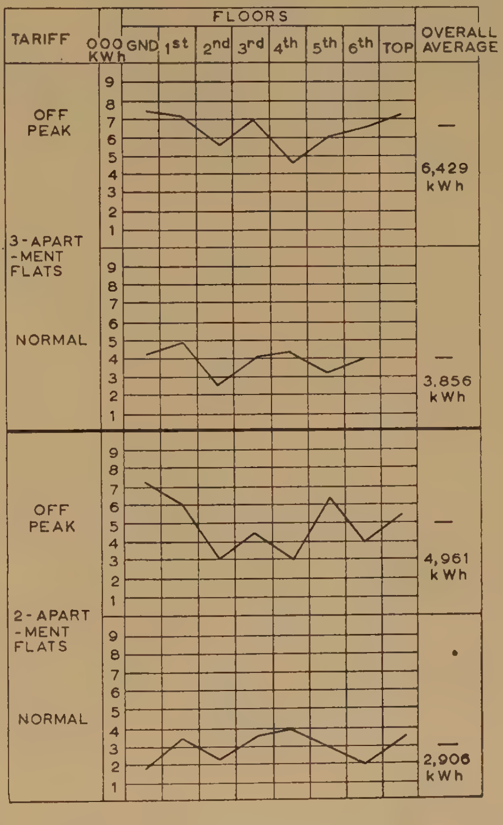


Fig. 12.—Kirkcaldy multi-storey flats.
Consumption of off-peak and normal electricity supplies, June, 1955–May, 1956 (inclusive).

The off-peak units include water heating as well as floor heating, and from a sampling test it appears that water warming accounts for 22% of the total off-peak consumption, the highest individual consumption being 50% and the lowest 13%. The habits of the various families differ considerably, some obviously preferring to meet the cost of a warmer dwelling, and the sample survey showed that hot-water usage also varied considerably.

It would be expected that the off-peak consumption of the ground- and top-floor flats would generally be higher than that of the flats on the intermediate floors. Fig. 12 shows a tendency

in this direction, although there is a definite deviation in both two- and three-apartment flats on the third and fifth floors. Another interesting point is that flats having a southern aspect would be expected to have a lower consumption than those with a western aspect. Analysis shows, however, that, on seven out of eight floors, the south-facing flats have the higher consumption. This may well be due to the fact that the south flats adjoin the drying rooms, staircase and lift well, and it is possible that this 'funnel' effect results in a cooling which offsets the advantage of the southern aspect. This would appear to bring out the need for some additional thermal insulation in walls subject to 'funnel' effects.

The actual results are, on the average, a considerable improvement on the estimates, and it is notable that, for average inclusive costs of 14s. 3½d. a week and 10s. 9½d. a week, the tenants of the three- and the two-apartment flats, respectively, obtained all their space heating, water heating, cooking, lighting and other fuel services for the twelve months. The tenants themselves have expressed entire satisfaction with the system.

The success of these flats has led Kirkcaldy to proceed with the construction of further blocks of floor-warmed dwelling houses, both of the multi-storey and maisonette type. A number of local authorities from England as well as Scotland have inspected the flats, and on the strength of the actual results, supported by the reactions of the tenants, have decided to construct electrically floor-heated multi-storey flats in their own areas.

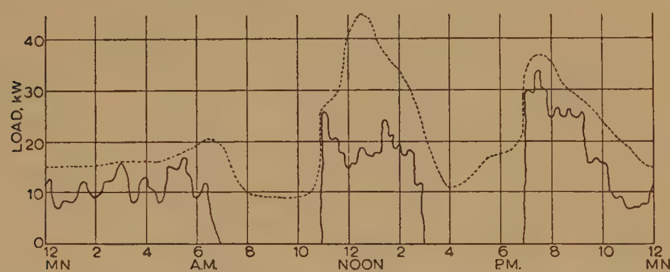


Fig. 13.—Typical daily load curves for 16 Kirkcaldy multi-storey flats.

– – – – Total load.
———— Off-peak load.

Fig. 13 is of interest from the electricity-supply standpoint. It shows, for a typical winter's day, the variation in load on the transformer supplying the block of flats. A second curve gives the variation in off-peak loading. The total installed off-peak load is 147·9 kW of floor heating and 144 kW of water heating. It will be noted that the total off-peak demand never exceeded 50% of the installed off-peak load. A further point of interest is the peak which occurs at midday, which must be mostly due to the cooking load.

(5.2.3) Dwelling Houses.

Multi-storey flats owned by local authorities have already been described. In this Section it is intended to refer to the extension of electrical floor warming to privately-owned dwelling houses. Many persons would like to enjoy the comfort of good central heating, but some cannot afford the high initial cost of the conventional method, and others dislike the disfigurement of radiators, pipework, etc., and perhaps hesitate at having to handle large quantities of fuel, ashes, etc.

Electrical floor warming, especially the solidly-embedded cable type, can cost as little as one quarter of the price of an orthodox central-heating system, and this, together with the fact that it is completely out of sight and requires no labour, explains why there is a rapidly increasing interest in this method of house heating.

The general pattern emerging with floor-heated dwellings is as follows:

(*a*) The ground floor of the house is of concrete and the upper floor of ordinary wooden construction.
(*b*) Living rooms, kitchen, hall and passages on the ground floor are provided with electrical floor warming. Bedrooms and bathroom on the upper floor are generally sufficiently warm from the heated ground floor, but any supplementary warmth is readily supplied from an electric fire connected to the ordinary supply.
(*c*) The lounge or main living room has the only fireplace in the house, although in practice it is not extensively used.

The private-house floor-warming installation shown in Fig. 11 has an electrical loading of 7·5 kW and an estimated winter-heating consumption of 11 000 kWh. An installation of this type costs about £180 complete with control equipment and installation costs. The cost of a comparable central-heating system, including the boiler building, would be about £500. A solidly-embedded floor-heating installation could have been installed for about £100.

The total annual costs of floor warming and water heating are in the region of £40–£45. Many persons would gladly meet costs of this order and be saved the trouble and even extra costs involved in operating orthodox central-heating systems.

(6) TARIFFS

The South of Scotland Electricity Board, being both a generating and a distributing authority, is able to view its tariffs directly in relation to generation costs of production. The incremental running cost of generation is a minimum when a large proportion of high-efficiency generating plant is in operation, and during the winter months generation costs are therefore at their lowest when the system load is low. They increase as less-efficient generating plant has to be brought into use to meet the higher loadings during the day time.

It follows that the most attractive off-peak tariff is justified for load restricted to the minimum-load period, which is between 1 a.m. and 6 a.m. A tariff with this limited availability of supply would be of little use practically, as very large and expensive storage equipment would have to be purchased to ensure that the heat stored during this short period would be sufficient to meet the needs of the following day.

An extension of the period during which off-peak supplies could be available would result in somewhat less efficient plant being brought into service, and the off-peak tariff would have to be appropriately increased.

The increased availability of the supply enables the storage equipment to be reduced in size and in cost, and, in examining the off-peak tariff situation, the South of Scotland Electricity Board gave careful consideration to achieving an economic balance between the lowest off-peak tariff on the one hand and the simplification and cheapening of the consumers' equipment on the other.

It was found that no single off-peak tariff could meet the position, and it was therefore decided that there should be three tariffs, two designed primarily for space-heating load, and a third tariff more appropriate for industrial and farming application.

The tariffs now in force in the South of Scotland District are as follows:

Tariff No. 1.—Where the supply is disconnected from 7 a.m. to 11 a.m. and from 3 p.m. to 7 p.m. daily, except Saturdays and Sundays, a charge of 0·52d. per kWh for high-voltage supplies or 0·55d. per kWh for medium-voltage supplies.

Tariff No. 2.—Where the supply is disconnected from 8 a.m. to 10 a.m. and from 3 p.m. to 5 p.m. daily, except Saturdays and Sundays, a charge of 0·57d. per kWh for high-voltage supplies or 0·60d. per kWh for medium-voltage supplies.

Tariff No. 3.—Where the supply is disconnected from 8 a.m. to 10 a.m. and from 3 p.m. to 5 p.m. daily, except Saturdays and Sundays, during the months of November, December, January, and February only, a charge of 0·62d. per kWh for high-voltage supplies or 0·65d. per kWh for medium-voltage supplies.

These charges are increased or reduced at the rate of 0·000 65d. per kWh for high-voltage supplies and 0·000 7d. per kWh for medium-voltage supplies for each penny by which the fuel cost is more or less than 60s. per ton at the South of Scotland Board's generating stations in the month for which such cost has been last ascertained.

In June, 1956, the fuel cost was 87s. 3d. per ton, giving a fuel-cost adjustment of 0·228 9d. per kWh for supplies at the ordinary voltage.

Floor-warming systems are generally supplied under tariff No. 1. The building has to have sufficient thermal storage to permit two 4-hour interruptions in supply during the 24-hour period, the periods of interruption being separated by a 4-hour boosting period in the middle of the day.

It has been found that large buildings have adequate thermal capacity to permit a 12-hour-on and 12-hour-off operation. When considering lighter buildings, such as private houses, a midday boost is undoubtedly necessary, since otherwise excessive cooling would occur during the day.

Off-peak tariff No. 2 is primarily designed to meet the need of electrode-boiler installations, where the user may prefer to pay a slightly increased charge rather than the capital cost of a thermal-storage cylinder or one of greater capacity.

(7) ECONOMICS OF ELECTRICAL FLOOR WARMING AS COMPARED WITH OTHER HEATING SYSTEMS

It has been stated that, as regards initial cost, the withdrawable type of electrical floor warming is generally cheaper than alternative heating systems. Where a solidly-embedded heating cable is acceptable, the initial cost is much less than any alternative.

As electrical floor warming gives more or less continuous building heating, it is eminently suitable for buildings that are used for long periods of the day. It is obviously unsuitable for heating a hall which requires only one or two hours' warmth occasionally.

Apart from exceptional cases coming within the last-mentioned category, it has been found that, in annual operating cost, electrical floor warming can generally compete favourably with other methods of space heating.

Surprisingly large numbers of people compare the estimated cost of electricity with the estimated cost of coal, gas or oil, leaving other heating costs, such as boiler operating wages and maintenance, right out of account. One main advantage of electrical floor warming, as indeed of all forms of electrical heating, is that, having met the cost of electricity, no other appreciable expenditure on heating is incurred.

The authors have found it of value to set out the estimated capital and annual operating cost of an electrical floor-warming scheme in the manner shown in Table 2. This does something to ensure that all relevant heating costs are taken into account when electrical floor warming is compared with other methods

Table 2

COMPARATIVE ESTIMATED CAPITAL AND OPERATING COSTS OF SOLID FUEL AND ELECTRICAL FLOOR WARMING BASED ON 210 DAYS AT NORMAL OUTSIDE TEMPERATURES

Electrical Floor Warming (submitted by South of Scotland Electricity Board)	£	£	*Solid-Fuel Heating* (as compiled by an architect)	£	£
A. *Installation.*			A. *Installation.*		
(i) Complete floor-warming installation, including all materials and installation work	19 800		(i) Central-heating boilers, radiators, pipework and fittings	25 000	
(ii) Expanded metal	750		(ii) Boiler room, flues, chimney, water-storage tower and fuel store	4 450	
(iii) Screed	2 000		(iii) Pipe ducts	1 500	
(iv) Attendant builder's work	450		(iv) Mason, jobbing, painting	1 000	
(v) Substation building (part cost)	500	23 500			31 950
B. *Capital Charges.*			B. *Capital Charges.*		
(i) Interest at 6% on £23 500	1 410		(i) Interest at 6% on £31 950	1 917	
(ii) Depreciation at 1·38% (30 years) on £23 000	317		(ii) Depreciation at 2·87% (20 years) on £26 000	746	
(iii) Insurance—Public liability	60	1 787	(iii) Insurance—Explosion with public liability	120	2 783
C. *Operating Costs.*			C. *Operating Costs.*		
(i) 1 290 000 kWh at 0·742 5d.	3 991		(i) Cost of fuel (500 tons)* at £5 per ton	2 500	
(ii) Repairs and maintenance	150		(ii) Labour: 1½ stokers	600	
(iii) Capital charges as B above	1 787		(iii) Oil, water and stores	60	
			(iv) Electricity for pumps, etc.	200	
			(v) Repairs and maintenance (2% on £30 950)	619	
		5 928	(vi) Capital charges as above	2 783	6 762
Annual total heating costs, £5 930			Annual total heating costs, £6 760		

* If only 400 tons are attributed to the solid-fuel heating scheme, electrical floor warming still shows an advantage of £334 per annum.
Note.—This statement has been revised to reflect interest and price levels in June, 1956.

of heating. The comparison shown relates to a building in the south of Scotland, and it brings out clearly the fact that, although the cost of electricity exceeds the bare cost of fuel, when all other factors are taken into account the electrical heating system is the more economical.

Table 1, read in conjunction with the details given in Section 5, shows that generally the annual floor-heating costs can be estimated with a fair degree of accuracy. The same cannot be said of other fuels.

Quite apart from the figures brought out in a comparative statement such as Table 2, electrical floor warming has advantages which cannot be expressed in a monetary way. It is undoubtedly the cleanest of all space-heating systems. The low operating temperature of the floor, coupled with the elimination of unnecessary air currents, enables internal decorations to be maintained in a fresh condition for a considerable period. The use of electricity does not entail the combustion of fuel on the premises, and there is therefore no emission of any kind to contaminate the air or harm the building exterior. No fuel or products of combustion have to be handled, and this not only eliminates noise and dust, but saves the considerable trouble sometimes involved in obtaining fuel when it is most needed during difficult wintry conditions.

In the south of Scotland floor-warming installations are giving satisfaction, both as regards comfort and cost. This is demonstrated by the fact that several authorities who have installed electrical floor warming have decided to adopt it for a second or subsequent building.

(8) CONCLUSION

A point has now been reached in the development of electrical floor warming when actual results are available to demonstrate that it comes fully up to expectations. The operating costs are reasonable, and the occupants of buildings express satisfaction with the standard of comfort obtained.

There is scope for more research into the characteristics of electrically heated buildings. Some research has already been carried out by the South of Scotland Electricity Board in collaboration with the Electrical Research Association and the Research Laboratories of the Central Electricity Authority, and the production of a full analysis of the various tests is awaited with interest. Further research should continue, particularly with regard to the comfort effect of radiant heat with low-air-temperature environments.

If there is to be a worth-while development in this new field, the electricity supply industry must be prepared to take the initiative in bringing the advantages of this method of heating before the members of other professions. Only too often the heating system of a building is decided without electrical heating being considered at all.

The development of off-peak load is greatly dependent upon the availability of suitable tariffs, and the authors from their experience would commend the system of off-peak tariffs now in force in the south of Scotland.

(9) ACKNOWLEDGMENTS

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It should be added that the views expressed in the paper are those of the authors and not necessarily those of the Board.

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DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE UTILIZATION SECTION, 11TH APRIL, 1957

Mr. J. I. Bernard: Towards the late summer of 1940 the Ministry of Home Security was trying to solve the problem of making people sufficiently comfortable in the block concrete air-raid shelters then building in London. When Mr. R. Grierson and I looked at one at Fulham, the air outside was quite warm, but there was a distinct sense of chill inside. I suggested to him that the concrete should be warmed, and later he had heating cables installed in the floor, with the very satisfactory results described in Reference 1 of the paper by Messrs. Moule and Stevenson.

Towards the end of the War I was interested in other thermal-storage methods of heating, and I went to Dublin to see what the Electricity Supply Board were doing. This was then mainly a hydro-electric undertaking, and the Board, being very conscious of the high capital charges, were looking for loads to fill the night 'valleys'. They investigated Continental types of thermal-storage heater. Mr. Bates went there just before I did, and subsequently I heard from him about the progress he had made in developing these thermal-storage block heaters.

The papers show that thermal-storage heating, by either of these methods, is entirely practicable.

There were some doubts whether these large masses of heated material would permit sufficient control to suit the vagaries of our climate. I think that has been shown to be practicable. Also it has been shown that, with either method, a very satisfactory degree of comfort can be obtained. This is undoubtedly due to the high radiation component mentioned in the paper by Messrs. Moule and Stevenson. In my view, when the heating is in the floor, there is some extra benefit above that normally obtaining when there is a radiation component in the source of heat, which enables one to run at a lower air temperature and so reduce the heat loss from the structure. This can be taken as a credit to electrical floor warming, making it, as Messrs. Moule and Stevenson have described, competitive with other methods. With regard to the effect of radiation on heat loss generally, a paper by Humphreys* shows very clearly the benefit obtained by having a high radiation component in the source of heat.

Both methods are successful, but there are some pitfalls to be avoided. With any method of electrical heating, buildings should have reasonable thermal insulation. The more there is the better, but builders are not easy to convince on this point, and with traditional methods of construction it is difficult to get a really satisfactory degree of insulation. It can be done in the way suggested by Messrs. Moule and Stevenson and in other ways which architects and builders are beginning to consider.

Floor heating, in particular, as Messrs. Moule and Stevenson state, requires a certain amount of insulation around the edge of the heated floor slab to prevent the heat from going sideways, and in some situations underneath it also, to prevent undue heat loss, for example, to very waterlogged subsoil or certain subsoils consisting of heavy clay.

Similarly, with solidly-embedded floor-heating cables, experience has shown that there are some pitfalls in the building construction. If the builder chooses to make a weak mix for the covering screed which goes over the cables and tamps it down, it is liable to crack at some later date. One cannot expect the cable to stand up to conditions like this.

However, we are learning by experience all the time, and there is no doubt in the mind of anyone familiar with the economics of electricity supply that, as Messrs. Moule and Stevenson point out, the standing charges are likely to increase still further and we must try to fill up the night valleys to a greater extent. Both methods of heating are simple and satisfactory ways of doing this. They are economical in capital expenditure and should enable us to supply all-electric houses at reasonable cost and a good load factor.

Mr. S. L. M. Barlow: These forms of heating are extremely desirable at present when there is an urgent need to utilize off-peak generating capacity. The papers achieve the useful effect of calling attention to the importance of producing properly designed installations, and of the necessity for the customer to know exactly what he is buying before installation. This specialist type of installation could quickly fall into disrepute if some control of this sort were not exercised. In my view buildings should not be heated entirely by systems deriving energy during off-peak periods, and a greater application of such systems, in addition to more satisfactory results, can be obtained by using off-peak loads for background heating. Heating installations designed entirely for off-peak supply can prove unsatisfactory in extremes of outside temperature or, for example, through heat loss from the excessive opening of windows.

With regard to the paper by Messrs. Moule and Stevenson, the withdrawable system is better. The little experience so far gained has shown that earth and open-circuit faults occur more readily in the solidly-embedded systems, often involving costly repairs. On the other hand, the D-shaped metal withdrawable system with metal diffusers is unnecessarily expensive, and it seems that the simple tube system containing the resistance cable gives all the heat diffusion necessary at a comparatively low cost. It may take a little longer to distribute the heat, but the rate of such distribution is largely dependent on design. Damage to decorations is an important factor not always taken into account in assessing the value of these forms of heating. Redecoration made necessary by convection currents above radiators and similar appliances can be a very costly item.

With reference to the paper by Mr. Bates, the present designs are ugly, heavy and some have surface temperatures which are too high. Two of these difficulties are easily overcome, and with the use of improved refractory materials the weight could be materially reduced. Research is particularly needed into the external design of the heaters, and it may well be that advantage can be gained by dispensing with the flat-top case, which is so easily used for the placing of inflammable materials. It might also be feasible to provide a mechanical means of dissipating the heat more rapidly over a shorter period if the user should require to do so.

At present, these heaters are too often sold from a catalogue, and it seems essential that they should always be sold with accompanying technical advice on their use and installation.

Mr. H. H. Bruce: In Table 2 of the paper by Messrs. Moule and Stevenson the costs of off-peak and central heating are compared sketchily, and there is an illuminating footnote to the effect that if you think of another number you get a different answer, but it is still in favour of off-peak heating. Electrical floor warming is not compared with floor warming using embedded pipes, but only with ordinary radiators or convectors.

The authors claim that floor heating has an advantage of 4°F over convective heating, i.e. 61°F with a warm floor is as good as 65° by convection. The average winter outdoor temperature is 41°F, and 4°F in a 20°F rise is 20%—which is not altogether negligible.

Perhaps the architect thought floor heating inappropriate in flats where what one tenant pays depends upon what other tenants do. At Kirkcaldy it would be comforting to have above you people who kept their carpets when they moved in!

* HUMPHREYS, O. W.: 'Economic Aspects of Electricity for the Domestic Heat Load' (read at the Institute of Fuel Conference, 1956).

At Kirkcaldy there is less than 4 kW of off-peak floor warming 'topped up' in severe weather by a 2 kW heater per flat on unrestricted supply. Is this the pattern for the future, and do other Area Boards encourage this procedure? If intolerable waste of electricity is to be avoided, off-peak heating with uncontrolled release must be limited to less than two-thirds of the space heating load, as, in fact, it is at Kirkcaldy.

Input regulators cease to function at 7 a.m. By then they have determined the heat supply for the following day. There is a 21% probability that it will average up to 2° F warmer than at 7 a.m., and there is a 32% probability that it will be 2–4° F warmer, but there is a 10% probability that it will be 5° F or more colder. If the system is designed for the 10% colder probability, there will be a waste of energy from overheating or window opening. The Kirkcaldy method, with one-third or more of the load on unrestricted supply, largely defeats the purpose of off-peak heating.

Mr. C. E. Mills: Fire risk is a problem to be considered with the heaters described in the paper by Mr. Bates, because they are in use at night when the premises are unattended, and consequently if a fault develops it will not be noticed. The heaters do not have a visual indication that they are operating, and the user may not realize that any considerable masking will cause a rapid rise in temperature which is capable of igniting inflammable materials. Also some limited degree of masking might occur in daytime with little consequence, but if this is maintained over night, the higher surface temperature could produce unsafe conditions.

I have investigated a few fires associated with these heaters and find that they nearly all occur at night, and often in severe weather. Typical causes have been masking of the top with rolls of cloth or paper. In other instances the heater has had a sack of wool placed in front of it, or inflammable material has fallen down the back. A large fire was caused by a heater being placed in contact with a fibre-board partition. Sometimes a contributing factor has been the omission or failure of a time switch, allowing the heaters to be charged for more than the eight or nine hours recommended by the makers. Occasionally faults in wiring have been suspected as the cause.

Abuse of the heaters by users will no doubt decrease as they become more familiar with possible hazards, but they should be made as inherently safe as possible. There are various ways of doing this, including the use of guards, thermal cut-outs, radiation screens or operating the heaters at a more moderate surface temperature. Some of the newer designs incorporate one or more of these features, which will go a long way to making these heaters safe under varying conditions of use.

Mr. H. C. Jamieson: The characteristics of floor heating with unrestricted heat supply are well known. Most of the heat used in the Kirkcaldy flats is unrestricted, and tubular heaters would give almost the same results.

The paper by Messrs. Moule and Stevenson does not deal adequately with the characteristics of floor heating where the heat supply is restricted. Heating engineers would need to know more of the effects of cooling floors on comfort before they could use this method with confidence.

In Reference 2 of the paper a drop of 5° F globe thermometer temperature in five hours was demonstrated, which agreed tolerably with the quoted drop of 2·6° F air temperature at Sighthill Health Centre. Such a drop is not acceptable in good heating practice. Solar radiation, occupants and lighting heat gains are too variable to be relied on uniformly to keep up the falling temperature. The conclusion was that restricted floor heating should be used for background heating only, and heating engineers would agree with this. They would welcome evidence to show that the method has a wider use.

Ventilation can be provided by off-peak electricity supply from hot-water thermal storage, and modern methods have cheapened this system.

Minimum external design temperatures are fully discussed in the Post-War Building Study No. 33 from which it has been shown* that the external design temperature for light buildings in the south of Scotland should be 22° F, and for heavy buildings 24° F, where a heating system with no overload capacity, such as electric floor warming, is used.

The 'valley' in the load curve (Fig. 1 in Mr. Bates's paper) from 11 a.m. to 3 p.m. is small, and would soon be filled by electric floor heating where power input is essential at this time.

The figures in Mr. Bates's paper for the reduction in output of storage heaters will give results similar to the figures quoted from Reference 2 for the drop in internal temperature.

Mr. W. Gilchrist: So far, evidence indicates that, from the comfort and psychological angle, people are satisfied with floor warming. No other system, whether it be ceiling warming, convector heating, enforced ventilation, etc., gives such satisfaction, but certain aspects of design and cost require attention.

It would appear, from the figures in Mr. Bates's paper that the load will be of the order of 15 watts/ft^2, assuming that the ceiling height is 10 ft. On the basis of 1·5 kW per 1 000 ft^3 he states that the average consumption is 1·1–1·2 MWh per annum per kW installed; but that is based on an installed load which is higher than the old traditional installed load for direct electrical heating of 1 watt/ft^3. Does this mean that the true figure in terms of our traditional method is nearer 1·5–1·6 MWh per kW installed?

In Table 1 of the paper by Messrs. Moule and Stevenson, consumption ranges from 1·1 to 1·8 MWh per kW per annum, and so it would appear that the figure derived from Mr. Bates's paper is low compared with that for floor warming.

There is no doubt that floor warming is the forerunner of the all-electric domestic multi-storey building. There is no other satisfactory way of providing the conditions required by the modern housewife. It is not possible by any other system of heating to ensure that people just pay broadly for what they require and what they use. Another important point is that the annual cost to the flat owners is less with this system than with central heating, since the tenants pay for what they use, and all the landlord has to provide is the capital cost of the installation.

In Table 2 there is an item of £750 for chicken-wire netting, but it has been proved conclusively that its use does not improve the heat distribution over the surface of the concrete.

With regard to one type of withdrawable system, are the authors satisfied that an aluminium duct embedded in a concrete screed will remain as a mechanical unit in that form over a number of years? Is there not a danger of chemical action affecting the aluminium in such a manner as to prevent the withdrawing of the cables.

Does the capital cost include that of the rising mains, of which presumably there are two sets—in fact, a complete duplicate electrical installation, including duplicate meters in each flat? Would the authors consider, as a suitable alternative, the use of one set of rising mains, one meter, and a special three-part block tariff, in which the excess energy over that used in the first two blocks is charged at the off-peak rate, the intermediate block being based on the normal consumption for cooking and water heating?

If we can solve the heating problem in the domestic building, it is inevitable that all other services in the house will be electric.

Mr. L. Shepherd: In the paper by Mr. Bates it is stated that heat is released from the fabric back into the occupied

* JAMIESON, H. C.: 'Meteorological Data and Design Temperatures', *Journal of the Institution of Heating and Ventilating Engineers*, 1954, 22, p. 465.

space. The heat is *in effect* released from the fabric and not *in fact*.

There has, in the short life of the development of these heaters, been too much muddled thought regarding the installed load to be used in any particular case. Having calculated the building heat loss, some designers install this load, some add 10%, or 20%, or 30%. The author adds 50%, which is a much more realistic approach where comfort temperatures of the order of 65° F are required. Admittedly, the figure could be reduced somewhat where lower temperatures are needed.

In general, there are two forms of control: those dependent upon temperature only, e.g. the room thermostat, and those which basically are dependent upon time, the length of the charging period being determined automatically by the external temperature.

If the installed load is too small and the means of control is a room thermostat or something similar, that thermostat will merely dictate a longer charging period. Provided that the external temperature is not down to the basic design value, the required temperature will be maintained, but under basic conditions the building will be short of heat. With the other form of control, however, once the installation has been designed on too small a heat input it will always be short of heat, because of the proportioning effect of the control.

In the paper by Messrs. Moule and Stevenson it is stated that the electrical loading of a warmed floor must be sufficient to permit the energy input during off-peak periods to meet the heat loss throughout the 24 hours, and that most installations are on tariff No. 1, which has an availability of supply of 15–24 hours. Even when making allowance for different rates of air change during the night, as opposed to the day-time, some surplus over the net building heat loss must be installed. A few calculations based on Table 1, however, show that no practical effect has been given to this, because the building heat loss is the same as the installed load.

Mr. P. H. Greer: In Ireland there is quite a large amount of thermal storage heating, particularly of the block type, as well as floor heating.

The heat given off by radiation follows the fourth power of the temperature difference; and thus the radiant storage heater acts as its own controller. The heater, being able to store the heat not so dissipated, carries it over until ambient temperature tends to decrease, when it will quickly operate to restore conditions.

A $1\frac{1}{2}$ kW block storage heater has, perhaps, as much as 12 kWh stored at the end of a normal discharge period.

Other speakers have mentioned the fire danger, and we find that the protection must be twofold. We now install a thermal link, which is a eutectic-alloy fuse wire, carrying the current to the storage heater. It is therefore a sensing element which covers all the vulnerable spots of the heater. It is sensitive to any obstruction to the heat output. We have also incorporated a spacing guard into the design of the heater. This prevents area contact between any heat obstruction and the hot surface of the heater, and by allowing a cooling convection current to develop, the stored heat is dissipated without fire risk.

With regard to electric floor heating, we are convinced that we must make full use of the storage medium. There are limiting temperatures which apply; for example, on the floor the maximum temperature should not be above 73°–75° F. The obvious answer is to distribute the element as much as possible throughout the storage medium, so that it is all at the same temperature.

I feel that a withdrawable system is very desirable, but generally it becomes very expensive because it is necessary to have a lot of conduit if the heating is to be well distributed. The solution we have used is to make the insulation on the cable loose, and not tight on the conductor as in a normal electric cable. Should a failure of the wire occur, it can therefore be pulled out and replaced.

Mr. K. W. Dale: In Section 7 of the paper by Messrs. Moule and Stevenson it is stated that 'surprisingly large numbers of people compare the estimated cost of electricity with the estimated cost of coal, gas or oil, leaving other heating costs, such as boiler, operating wages and maintenance, right out of account'. This surprises me. I wonder, for instance, whether the estimated and actual running costs of the various schemes, other than that in the hypothetical Table 2 of the paper, include all the items shown in B and C. For instance, do the costs of 14s. $3\frac{1}{2}$d. and 10s. $9\frac{1}{2}$d. a week quoted for Kirkcaldy include these items? It seems probable that they do not, and that these sums are what tenants have paid for electricity consumed.

If so, it might logically be argued that the cost of heating to the tenant, using solid or oil fuels, should be just the cost of the fuel. For some time I have felt that the cost of the installation and maintenance of any type of heating installation should be a direct charge in the rent and not a running cost. If this achieved nothing else it would avoid the use of 'red herring' Tables, such as Table 2. Whilst I do not doubt that the authors find it useful to prepare them, I wonder, in fact, what use they serve.

If we accept the authors' figures, the solid-fuel plant burns 500 tons of coal to produce 1·29 million kWh, whereas at the power station 700–800 tons will have been burnt. From the national viewpoint this is surely appalling.

The authors state that the habits of people differ with regard to heating and hot-water service. How do they vary at Kirkcaldy?

At St. Mungo's School the authors state that the sickness rate has been extremely low, but extremely low in relation to what? Do they mean in relation to schools without heating or schools with conventional forms of heating? Such statements should be qualified, or they can be extremely misleading.

Miss M. V. Griffith: The B.E.A.I.R.A. has had the benefit of collaboration with the authors on floor-heated buildings in Scotland over the last four years. Continuous recordings of surface, air and globe temperatures, solar radiation, wind speed and external temperatures have been obtained. Daily readings of consumption have been available.

The floor-surface temperature in the early morning, even in well-insulated buildings with the air temperature thermostatically controlled at 65° F, is usually well over 80° F. The high early-morning temperature is, however, useful in adding to the heat stored in the walls, and there have been no complaints of discomfort.

The temperature difference across carpets varies with the insulation of the room walls and the external temperature. Values higher than 10° F may be found with low external temperatures. We have recorded temperatures as high as 95° F below carpets.

Changes in emissivity are compensated, because the floor temperature varies to satisfy the air thermostat.

It is most important to take the local variation in external ambient temperature into account when designing systems. Methods of control need further study. Nearly all the cases of bad performance known to us have been due to inoperative thermostats or their wrong positioning. It is better to set the thermostat out from the wall so that the air has access to the sensitive element.

The present method of calculation of the rate of heat loss from a building is not satisfactory for the estimation of consumption. In simple buildings it works quite well, but in others the actual consumption per deg F difference between internal and external air

*

temperatures is much less than the estimated value. This does not apply only to floor heating. Satisfactory thermal performance with many floor-heating systems is, however, obtained by installing a loading which is equal to the steady state of heat loss, calculated using the published coefficients, with 35° F difference between the inside and outside air temperatures. I should like to support the authors in emphasizing this. Sometimes the method does not work, but this is probably due to the effect of the soil beneath the building.

One reason for the higher consumption in the first year of operation is that a higher air temperature is called for to offset the cold feeling of the walls.

There are many points on which comment would have been interesting. These would include the effect of the thickness of concrete on storage in practice, the flow of heat in multi-storey buildings, and the effect of wall panels and auxiliary heating on the behaviour of floor-heating systems.

Mr. R. B. Rowson: Apart from the advantage of avoiding guards, low surface temperatures on storage heaters are an advantage in tending to make them self-regulating, thus avoiding the overheating which occurs when a warm day follows a cold night.

At present, owing to purchase tax, block heaters are unlikely to make much headway for domestic use. This is most unfortunate, as there seems no other way of providing off-peak heating for the 12 million existing houses.

I would support Mr. Bates's plea for not offering block heaters when premises have insufficient heat storage capacity. This should also apply to floor warming, and in this connection Ghai and Sundaram's formula* might help in specifying suitable premises.

Control of off-peak heating is most important, both for comfort and economy, particularly at the ends of the heating season. Our experiments showed that the QA/QR method was only suitable for a continuously available supply. The cam-adjusted thermostat works well, but the simpler one is adjusted from outside, while the capillary-tube model involves installation difficulties. Neither is responsive to wind, since they are not heated. Fig. A shows an improved arrangement which is extremely flexible and is responsive to wind. We have also developed an additional control responsive to rate of change of temperature, which is needed in high-altitude valleys.

* Ghai, M. L., and Sundaram, R.: 'Selection of Outside Design Temperatures for Heat Load Estimation', *Transactions of the American Society of Heating and Air-Conditioning Engineers* 1955, 61, p. 169.

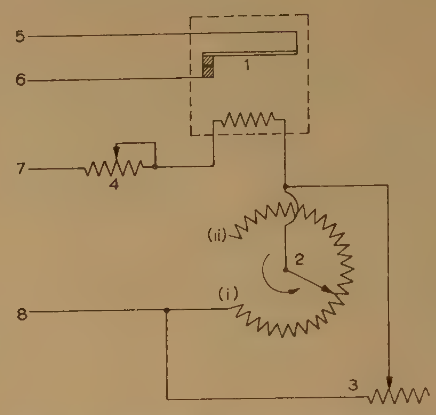

Fig. A.—Improved control arrangement.

1. Outside thermostat set at 60° F, housed in metal box and fitted with 20-watt heater.
2. Indoor rotary potentiometer driven by synchronous motor. At position (i) shortly before commencement of off-peak period. At position (ii), 90 min before the end of the period.
3 and 4. Manual setting adjustments.
5. To time switch.
6. To contactor coil.
7. To phase.
8. To neutral.

With regard to heat flow from a warm floor, I believe that the coefficient of 0·4 does not allow for the air movement, and thus the ratio of radiation to convection during periods of occupancy may be very different from curve (*c*) in Fig. 5 of the paper by Messrs. Moule and Stevenson. The hours of availability mentioned are longer than those which would be offered by most Boards, and it would be useful if the authors would publish specimen load curves in their reply.

Mr. S. F. Adcock (*communicated*): Two points in the paper by Messrs. Moule and Stevenson need further clarification; they concern the actual installed load and the estimated and actual consumptions.

Table A is prepared from the information supplied in the paper. Cols. 1 to 4 are taken directly from Table 1 of the paper. Col. 5 is the installed load required to balance the heat loss if the acceptance of load is unrestricted. Cols. 6 and 7 give the load which should be installed to balance the heat loss when calculated in accordance with the details given in Section 4.1, and, using the restricted periods during which energy is available, as quoted under tariff Nos. 1 and 2 in Section 6.

Table A

1	2	3	4	5	6	7	8	9	10	11
	Type	°F rise	Heat loss		Required heating load based on		Actual load installed	Annual consumption on degree-day basis		Estimated annual consumption quoted in Table 1 of the paper
			B.Th.U./h	Equivalent kW	Tariff 1	Tariff 2		Minimum 3 250° F days	Maximum 4 500° F days	
					kW	kW	kW	MWh	MWh	MWh
A	Industrial ..	32	975 060	286	428	344	286	700	970	406
B	School.. ..	30	1 300 000	380	580	455	390	990	1 370	650
C	Public services	35	870 000	255	383	305	262	565	785	393
D	School.. ..	27	662 190	195	290	234	218	562	778	337
E	School (Stage 1)	42	760 850	224	343	270	230	416	578	381
F	Public services	32	304 110	89	133	107	101	217	300	180
G	Fire station ..	32	238 000	70	104	84	70	170	235	110
H	School.. ..	35	2 750 000	810	1 200	970	860	1 800	2 500	1 290
I	Industrial ..	32	266 400	78	117	94	110	189	265	127
J	Industrial ..	32	3 000 000	880	1 318	1 050	880	2 140	2 950	1 320
K	Domestic ..	32	560 000	164	246	196	164	400	556	256
L	Domestic ..	32	510 000	150	224	180	148	360	505	250

In col. 8 is shown the actual load installed as quoted in Table 1 of the paper. It will be noted that, in all cases with the exception of I, the actual installed load is approximately equivalent to that which is required to balance the heat loss when acceptance of energy is unrestricted. It is concluded, therefore, that generally no allowance has been made in the design of these installations to cater for the restricted hours imposed by tariff No. 1 or 2, although it is suggested in Section 6 that floor-warming systems are generally supplied under tariff No. 1, and, in the second paragraph of Section 4.2, that account must be taken of the restricted periods of supply in arriving at the total electrical loading.

In Section 4.3, two methods are quoted by which the seasonal consumption may be calculated. Cols. 9 and 10 of Table A show the consumptions of the various buildings, calculated on the deg F-day basis for the extremes of conditions encountered in Great Britain.

Col. 11 shows the estimated consumptions for the various buildings as quoted in Table 1 of the paper. It will be observed that, in all cases, these estimated consumptions are appreciably lower than the consumption calculated for the most favourable conditions.

Actual consumptions are only quoted in respect of a few installations, and it is noted that these are broadly in accord with the authors' estimated consumptions. It would appear that there is some discrepancy between the figures quoted in Table 1 and the results obtained by calculations, and the authors' comments would be appreciated.

Mr. L. B. S. Golds (*communicated*): Mr. Bates refers to the importance of time control and suggests the use of a time switch which is either escapement-operated and electrically wound or synchronous-motor operated with a spring reserve mechanism. Experience has shown that the former type is not as satisfactory as the latter, because the time-keeping is under the control of the escapement during the whole period of use, whereas the escapement in the latter type controls the time-keeping only during the rare occurrence of a supply failure. It should be remembered that, while an escapement control is satisfactory over limited periods of 2–3 years, maintenance is essential after that period if accurate time-keeping is required. Therefore, it is preferable to rely upon the synchronous motor, which requires less frequent maintenance to maintain proper time-keeping under normal conditions.

Referring to Section 10, I wish to emphasize the importance of transferring load from day-time to night-time for the reasons which Mr. Bates has given. There would appear to be no fundamental reason to preclude the charging of domestic users on a day-time demand basis, so that the storage heater would not attract a charge in respect of demand. This country cannot afford to provide an electricity service in which a typical winter demand curve is similar to that shown in Fig. 2. Clearly, some major effort has to be made to fill, at least partially, the night-time valley.

My final point concerns the problem of the ventilation of a heat-insulated room—an aspect which Mr. Bates has apparently disregarded. This is important because a certain amount of heat must be lost through ventilation during the day, and heat may be required in the late afternoon or early evening when the stored heat is nearly exhausted. I should be interested to have Mr. Bates's comments on the problem.

Dr. W. H. Marmorek (*communicated*): My colleague, Mr. L. Weaver, and I were responsible for the design of a one-storey factory in Shrewsbury with a floor area of 37 000 ft^2. Considerable thought was given to the most suitable method of space heating, and it was finally decided to use an electric floor-warming installation of the solidly-embedded type. The decision to proceed with this kind of installation, which is believed to be the largest of its kind in the Midlands, was based on the estimated consumption of current, submitted by the engineers responsible for the installation.

Recorders were installed to provide a graph relating outside and inside temperatures, and the Midlands Electricity Board had a recording instrument showing the hours during which electricity was, in fact, being used. The results so far obtained, which cover only one heating period, have been very satisfactory, from the point of view both of comfort and economics. The inside temperature was maintained, in spite of considerable fluctuations in the external temperature, and perhaps the architects may claim a little credit, since this was largely due to the good thermal insulating qualities of the building. This form of heating is ideal, and we are planning to use same system in another factory of similar size.

Mr. G. V. Sadler (*communicated*): The paper by Messrs. Moule and Stevenson deals generally with floor-warming installations in commercial and domestic buildings, and the following information on a large factory-building installation may be of interest.

The installation, comprising heating cables in steel tubes, with access at each end of the tube for cable renewal, has been installed in a factory building 400 ft long × 80 ft wide. The building is of normal steel construction, fitted with patent sheeting and continuous glazing along the roof and on one side, the other side being open to existing buildings. The height of the building from floor to eaves is 42 ft.

The total loading is 510 kW, and the system is divided into four sections, each with its own floor and air thermostat control, the whole installation being controlled by a thermo-time regulator of the type illustrated in Fig. 8. The installation was put into service at the end of December, 1956, after a pre-period of two months for gradual build-up.

Since the floor is subject to heavy loading and used for machinery assembly, the full depth of concrete was laid at one time, the heating tubes being laid in position at the right height beforehand, and supported on concrete plinths at intervals.

The system has proved very satisfactory in the two months subsequent to December, and the average daily consumption was 3·6 MWh. The system is operated entirely off peak, the on-peak hours being 8 a.m. to 12 noon, and 4 p.m. to 6 p.m.

The factory concerned had various types of heating installed and in use for many years, but it is of interest to note that the floor-warming installation in the new factory extension is the only one which has evoked appreciative remarks from the workers employed.

Mr. P. Schiller (*communicated*): Before the advent of nuclear power, thermal-storage heating could be criticized from the viewpoint of national coal economy, since, even if all the night load were eventually generated at 30% thermal efficiency, distribution and storage losses would reduce this to, say, 25%, or about half of what could be obtained with a modern central-heating installation. This aspect can, perhaps, now be ignored. However, since off-peak heating is bound to consume more electricity than direct-acting heating, and the equipment is more expensive to install, a larger differential between the price of normal and off-peak supplies than is now available will, in most cases, eventually prove indispensable, not only to promote this form of heating, but also to avoid consumers drifting back to direct electric heating.

To increase the differential, the charge for normal supplies will need to be raised, since present off-peak rates already tend to leave insufficient margins in respect of additional distribution capital charges. For instance, dwellings with over 3 kW floor-heating load, electric cooking and supplementary heating in very cold weather could easily set up after-diversity maximum demands

of 5 kW per dwelling, especially with a midday 'boost', whereas hitherto not more than 3 kW has been envisaged as the ultimate aim in the design of new distribution systems, and existing systems are designed for much lower demands. If off-peak heating for domestic, commercial and other premises were indeed developed on a very large scale, it would soon be found that midday 'boosts' also create new h.v. system peaks, especially on the national Grid system.

I feel that the practicability of applying electric floor-heating to council-type dwellings needs much more consideration, since a large proportion of tenants of such dwellings must be assumed to be disinclined to pay for continuous heating. There is a danger that substantial low-load-factor on-peak loads might emerge owing to change-over to electric fires, etc.

Mr. A. Wilson (*communicated*): In the paper by Messrs. Moule and Stevenson it does not seem that adequate attention has been given to the true comparison between equal-size space-heating systems fired by a variety of fuels. From Table 2 calculation would appear to show that the installed heating capacity of the electrical system was the equivalent of some 950×10^3 B.Th.U./h whilst that of the solid-fuel heating system was close on $1 \cdot 6 \times 10^6$ B.Th.U./h. For direct comparison, it would therefore seem necessary either to increase the capital and running costs of the electrical system by some 60% or to reduce the solid-fuel system by an equivalent amount. If the former is done the capital cost of the electrical system would be increased by some £12 000, the capital charges by some £1 050 and the operating costs by some £3 000. This would give a revised annual total heating cost of £9 000, or an increase over the solid-fuel system of some £2 000. Under such conditions the desirability of using an electrical floor-warming system does not appear to be sound.

With regard to the operating costs, the allocation of 1½ stokers on what is presumed to be a full-time basis at a total of £600 per year is rather high. In fact, a semi-automatic central-heating plant should not be expected to require more than the equivalent time of perhaps half a stoker. I think that a comparison should have been made with a liquid-fuel-fired system, using an oil of some 950 seconds Redwood No. 1 viscosity and utilizing a fully-automatic boiler plant.

I feel that both this paper and that by Mr. Bates seek to justify the use of electricity for space heating in order to balance the low night load which obtains on the national Grid. This, in turn, affects the overall base load and thus the economics of power generation.

Encouragement of the use of a heating medium which has only been generated at a net efficiency of, say, 24% is to be deprecated, for a much greater effect on both efficiency of plant operation and utilization, to say nothing of creature comfort, would result from the planning of large district heating schemes, such as have been used on the Continent and elsewhere for many years. These could be expected to give increases of perhaps as much as 20%, against the more likely figure of 4–5% if almost perfect balance were achieved between day and night generating loads which obtain at present.

[The authors' replies to the above discussion will be found on page 446.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 25TH FEBRUARY, 1957

Mr. E. C. Lennox: The two papers have come at a particularly interesting time. The Clean Air Act has only just been introduced, and local authorities throughout the country are giving serious attention to the setting up of smokeless zones. Storage heating by electricity must fulfil a useful function in carrying out problems relating to the Act.

The first essential is that commercial staffs of Electricity Boards should be trained in problems arising from heat storage and background warming. The method of calculating heat losses in buildings must be known, and evaluation of various types of building materials must be appreciated. Consumers must have the best advice in this matter. They must also fully appreciate the relation between comfort heating and air temperature as considered in Section 3.1 of the paper by Messrs. Moule and Stevenson. Fig. 11 makes no reference to insulation under the concrete floor. Advice should be given as to when and where such insulation is necessary and the best type of insulating material to use in order to avoid the difficulty which follows the quick absorption of water from the concrete.

The authors are to be congratulated on their efforts in connection with the Kirkcaldy flats. The problems which arise from the application of a suitable tariff include the fact that the daily load between 12 noon and 2 p.m. is increased by the advantage taken of the four-hour mid-day 'boost' on the floor-warming installation. Undoubtedly this coincides with the normal cooking load, and although it is off peak for the national system, it creates an unduly large peak on the local system, thereby attracting considerable capital commitment in transformer plant and copper. This is especially so on a Sunday when cooking load causes the maximum peak of a week.

Could the authors give the results of their experience in the method of laying concrete? The concrete floor comprises

(i) Hard core.
(ii) Damp-proof course (d.p.c.).
(iii) Structural floor.
(iv) Cables.
(v) Floor screed.

Information should include the dimensions of the various concrete layers and the time element in the laying of the various layers, e.g. it would appear that cables should be laid on structural floor within a day or so of its completion and that the floor screed should be laid immediately following so as to ensure a keying of the floor screed to the structural floor. Builders will find difficulty in carrying out this procedure unless they leave the hard core without d.p.c. until practical completion of the building. The general method appears to be to lay the structural floor, leaving the final floor screed as the last effort in the building, to avoid workmen damaging the floor surface. On the other hand, from the point of view of drying out, it seems essential that the structural floor, cables and floor screed should be laid in the early stages to give a maximum drying-out period.

With regard to transportable thermal-storage space heaters, I suggest that it is desirable to advise the consumer to have a separate control, in addition to the Board's time-switch control which restricts supplies to off-peak hours, or the space heater will be in general use much longer than is necessary to meet his needs having regard to building heat losses and varying weather conditions.

The considerable variation in cost in producing 65° F indoor design temperature in comparison with, say, 55° F should be more generally appreciated. Generally consumers may well find it cheaper to adopt low indoor design temperatures, and to use 'live' radiators to give adequate comfort conditions during the short hours of use of the rooms. This creates a supply difficulty, as such consumers obtain off-peak supply at marginal rates, and, in addition, create a peak in the short hour use of 'live' heating.

To overcome this problem it seems essential to allow 'live' heating in addition to storage heat in the same premises, the

consumer paying, in addition to the normal rate, a fixed charge to meet the Board's estimated charge at peak.

Mr. F. E. Heppenstall: The statement in Section 7 of the paper by Messrs. Moule and Stevenson that the heating costs of other forms of fuel could not be estimated with accuracy is disproved by the research which has been done on the subject over a number of years by heating engineers.

In considering the annual heating costs of buildings it is essential that each case should be considered on its merits, since circumstances differ in most cases.

The figures in Table 2, which are to illustrate the comparative costs of heating a school, are inaccurate for the following reasons:

The fuel consumption equivalent to the alternative electrical consumption would be 300 tons of solid fuel.

The cost of stoking should not be included, as this is always carried out by the caretaker, who has to be on the premises in any case.

While the life of boilers can probably be taken as 20 years, the life of the rest of the central heating installation, radiators, pipework, etc., should be taken at 30 years.

The life of the electric heating cables has been taken as 30 years, although, of course, there is no evidence that this is a true representation.

The figures published by the Electrical Development Association* gave the annual average consumption for electric fires for heating schools as 110 kWh per 1 000 B.Th.U. heat loss, with tubular heater installations at 200 kWh and floor-heating installations at 510 kWh per 1 000 B.Th.U. heat loss. The figures given in the paper for floor-heating installations are only slightly below the 500 kWh figure. Using the North Eastern Electricity Board's tariffs for direct heating (on-peak) at about 1½d. per kWh and the off-peak heating at 0·85d. per kWh, it is obvious that the lower consumption of the electric-fire installation or the tubular-heater installation makes it a better economic proposition as it is much less than half that of the floor-heating installation. For example, the school in Table 2 could have been heated electrically with a consumption of 500 kWh at a cost of £3 180 at the ordinary heating tariff. This indicates the need for a lower tariff for off-peak heating if it is to be encouraged.

I would like to emphasize the importance of getting proper advice from qualified heating engineers, who will consider all forms of heating for any particular building.

Mr. H. Ainsworth: With regard to the design of storage heaters, I think that, with advantage, further fibre insulation should be installed in the back of the heaters to reduce heat loss into the wall and thus permit further radiation and convection emission from the front and sides.

In the paper by Mr. Bates, there is reference to the danger which may arise from excessive surface temperatures. Certain of these appliances are now fitted with a thermal cut-out to prevent this dangerous situation arising, but it would appear to be more advantageous if a resettable type of cut-out could be fitted.

The reference in Section 3 to the blend of 55% radiant and 45% convection heating is of the greatest importance. It is a very important factor in deciding on the position when installing heaters, particularly in large installations. A small number of heaters should be installed in the immediate vicinity of personnel to take full advantage of radiation and thus permit the operation of a lower air temperature with consequential saving in running cost.

The reference to charging hours is one of the important features in any thermal-storage heating installation. While in normal cases, such as offices, the ideal method of charging will be the suggested 9 hours to switch off at the latest possible off-peak time, this arrangement may be very misleading in certain types of installation, particularly clinics, hospitals and schools operating in the evening, and I would suggest that the charging period should be associated with the occupational use of the premises and, perhaps more important, the heat-loss characteristics of the building.

The control of storage heaters is all-important, and the question of consumer-adjusted time switches is worthy of much consideration, particularly to the small user. In the Sub-Area with which I am associated we have supplied a schedule to consumers recommending switching hours varying with winter months, in the hope that the consumers will adjust their own time switches when required. It would appear that the author has little faith in the ability of consumers to carry out this operation. Nevertheless, with such a method, there is considerable advantage to a salesman who may then predict with some accuracy the running cost. The alternative would obviously be some method, such as the QA/QR thermostats, which, however, would be a high cost for a small installation, and I would suggest that a time switch with a variation of a solar dial to be calculated on a degree-day basis is worthy of special consideration.

The reference in Section 4 to surface temperatures is extremely important, particularly where children are concerned, although I do not agree that the introduction of fire guards is a suggestion of danger. The recent regulation with regard to fire guards on radiators does not appear to have had any adverse effects, and I cannot see that there should be any difference with storage heaters.

Mr. F. D. Parker: With regard to the paper by Mr. Bates, I am glad that the author has emphasized the importance of installing an adequate number of storage heaters. Owing to their size and cost, the temptation to cut the loading is very great and unfortunately practised by those who should know better.

From my experience, where the building has reasonable thermal capacity, an additional 33⅓–50% on to the calculated heat loss will give satisfactory results, provided that the heaters can be charged to a maximum of 11 hours per day during exceptionally severe weather.

It is essential that the building possess reasonable thermal capacity, and here the author's calculation of temperature drop is interesting. For general applications, this could take the form of a curve showing the temperature variation for different ratios of thermal capacity of the structure and calculated heat loss for, say, a 9-hour occupation period. With this type of installation it is very important that the user be advised that a variation in temperature will take place.

I am sorry that the author has not dealt more fully with the estimation of consumption. Estimates based on kWh per kW are misleading without knowledge of the calculated heat loss. I have found that, for installations controlled by outdoor/indoor thermostats (QA/QR type), with settings of 53° F and 64° F, adjusted deg F-day figures of 2 700–3 000 for the full heating season in this area are satisfactory. This allows for heat gains and somewhat lower average maintained internal temperature.

With regard to the paper by Messrs. Moule and Stevenson, I am interested in floor warming for multi-storey flats. Tariff No. 1, available in Scotland, provides a very generous midday 'boost' which may not be enjoyed elsewhere. In the absence of such a midday 'boost', would the results obtained at Kirkcaldy have been possible? How would this have affected the depth of screed to be provided in the intermediate floors and other structural conditions?

One of the chief difficulties with floor warming is ensuring firm adhesion of the screed to the structural floor. Does the presence of a heat diffuser make things more complicated? For instance, does it introduce an undesirable time delay between the completion of the structural floor and the screed? Is this heat diffuser really necessary? Have the authors any figures for

* Electrical Development Association: 'Electric Space Heating', April, 1955.

temperature gradients with various thicknesses of screed with and without a heat diffuser and with different cable spacings?

No mention is made in the paper of expansion joints. Are these necessary, and if so, when?

Mr. E. H. Sadler: It is apparent from their references to private dwellings and maisonette flats that the authors expect to connect these loads to their ordinary residential-area low-voltage networks and charge kilowatt-hour rates that are only 0·03d. higher than those for an h.v. supply with the substation on the building site.

Fig. 1 of the Utilization Section Chairman's Address* shows a domestic load curve with its short 8.30 a.m. peak, a similar or higher 4.30 to 5 p.m. peak with its very slow decline until 10.30 to 11 p.m., and it is stressed that 'it is of particular significance that this high demand is maintained for the remainder of the evening'.

In the paper by Messrs. Moule and Stevenson, the authors are apparently prepared to superimpose a floor-heating load of 3–4 kW actual demand per house on the already substantial evening load, and to supply this at a price equivalent to their h.v. off-peak tariff with only 5% addition for losses. Since this load will be 100% on-peak as far as the l.v. network cables, transformer and the local h.v. system are concerned, it will inevitably involve l.v. network reinforcement at a cost between £15 and £25 per kW of demand at the substation, and yet one of the loads that necessitates this reinforcement is making no contribution at all to the l.v. capital charges that are incurred. On the authors' demand and consumption figures of 2 904 kWh per kW of effective demand these costs amount to 0·1–0·16d. per kWh used for floor heating.

If minimal off-peak rates are to be charged it is most important that this load should be off peak to every part of the system involved in its supply. In order to justify the charge that the authors offer, namely the h.v. rates adjusted for losses, for l.v. network supplies in residential areas, the evening floor heating should not commence until 10.30 p.m. However, on a city network the same load could be connected after 6.30 p.m., and it is important that this point be borne in mind in the formulation of tariffs.

I consider that, with the permitted hours specified in the tariffs, the authors' quoted prices are inadequate when supply is obtained from l.v. networks in a residential area.

Mr. G. P. Cundall: The thermal efficiency of a coal-fired power station is about 30%. The efficiency of conversion of electricity to heat can be 100%, and so the maximum thermal efficiency of an electrically-operated heating installation is 30%. The heat losses through the night of an off-peak-heated installation exceed those of the conventional type, and in the paper by Mr. Bates it is suggested that, to allow for this, the loading of the thermal-storage heaters should be 50% higher than that for conventional heaters. Using modern solid-fuel boilers conventional installations can be operated at 60% thermal efficiency. Their consumption of fuel is therefore less than half that of a power station providing off-peak heat. Even if electricity were sold for off-peak heating at a price covering only the fuel cost, the charge would be over twice the cost of the amount of coal necessary. Electricity will be economical only when the difference in overhead charges offsets this greatly increased fuel cost. Selling electricity at the bare cost of the fuel consumed will not reduce generating costs generally.

The reduction in system load at midday is small compared with that at night. The most economically designed thermal-storage system will take advantage of the midday 'boost', and this will mean that the midday 'valley' will soon be filled. Some assurance is needed from the Electricity Boards that, when a midday 'boost' has been allowed at the design stage of an installation, it will not be subsequently withdrawn.

It would be advantageous if the heat-storage capacity were stated by the manufacturers of heaters, say in British thermal units available in cooling to 65° F from the normal peak surface temperature.

Surface temperatures exceeding 180° F appear to be dangerous. It would be interesting to know whether any fires have resulted from an accumulation of waste material behind heaters which operate at high surface temperatures.

[The authors' replies to the above discussion will be found on page 446.]

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 16TH APRIL, 1957†

Mr. K. W. Ballamy: The paper embodies the results of a number of years' pioneer work by the authors. Those working in this relatively new but ever-expanding field of electrical utilization realize the importance of all the data compiled, for, unlike so many branches of electrical engineering, the use of normal laboratory-type tests here gives only a very limited supply of useful information. Methods of design and control, as can be seen, have improved considerably, but bearing in mind the flexibility available with electrical utilization, there is undoubtedly considerable scope for development. The possibilities for the future are therefore very great, provided that they proceed on the correct lines.

I feel, therefore, that a responsible outlook should be taken by electrical engineers, for if this type of heating is not properly designed by specially trained personnel, there are many pitfalls which could bring it into considerable disrepute.

Brief mention was made of external controllers, but I should appreciate any comments by the authors on two particular aspects. First it seems that they should be most reliable in operation, for in some cases they are responsible for handling very large schemes. It would be interesting to know what troubles have arisen in the types tried, and if possible to have rather more information on the Health Centre quoted in the paper. Secondly, it seems that, with floor warming as compared with thermal-storage block heaters, external controllers should be applied with rather more caution. Since thermal storage is considered more on a seasonal than day-to-day basis, underheating could be encountered in some cases, such as new buildings drying out, or buildings which, owing to their flimsy construction, have a high loading relative to the storage available.

Finally I should like to consider some points which really determine the overall efficiency with which the electricity is utilized for heating the building. The transfer of electrical energy into heat energy is well established as 100%, but from then onwards the main problem is to ensure that a maximum of this heat is utilized directly for producing comfort in the areas concerned. One of the most important factors covering this is the proportion of heat transmitted from the floor to that lost downwards and around the edges of the concrete-floor slab. For this reason, the organization with which I am connected normally recommends insulation around the edge of the heated slab. Furthermore, the equipment embedded in the floor is especially designed to ensure that heat is diffused evenly across and towards the prime transmitting surface. There remains, however, the possibility of loss of heat downwards, and although we feel that, in most cases, this is negligible, there are certain

* GIBSON, H. J.: 'Utilization Section: Chairman's Address', *Proceedings I.E.E.*, Abstract No. 2270, February, 1957 (104 A, p. 11).

† This discussion refers to the paper by Messrs. Moule and Stevenson only.

site conditions, e.g. with a high water table, which could make this loss very appreciable. Since these must have been encountered in Scotland, I would like the authors' comments both on any investigations they make at a site considered for floor warming as well as any subsequent precautions recommended.

Mr. M. Bolser: Have the authors any experience with floor-heating installations in churches or similar buildings, where the use of the premises is such that heating is only required in off-peak periods, i.e. Saturdays and Sundays? The heat-storage capacity of the sub-floor is not required, and it is therefore necessary to provide overall thermal insulation between the sub-floor and the heating screed. I have designed church-heating installations using the heating screed purely as a radiant panel, and these have proved very satisfactory.

The electrical heating engineer must specify to the architect his requirements for the construction of the floor. Matters such as heat insulation, screed thicknesses, damp-proof membrane and floor finishes should be agreed by the heating engineer and the architect at the design stage, since the success or failure of any scheme depends, to a large extent, on these factors.

The thermo-time regulator described in the paper can be very useful in reducing consumption during periods at the beginning and end of a heating season as 'simmering' is prevented, but have the authors any experience of underheating caused by a very rapid fall in night temperature when using these regulators?

Mr. C. R. Taylor: The authors refer to different methods of controlling floor-heating installations, but it would seem that, with a floor temperature of 73° F, the system is almost self-regulating, provided that floor thermostats of sufficient sensitivity can be installed in such positions that they will accurately represent the temperature of the mass of the floor. This, perhaps in conjunction with an air thermostat, might be expected to give effective control in a large proportion of the installations. It would be interesting to know the authors' experience of simple control of this type.

An orthodox calculation of the type shown in Table 2 serves a useful purpose only when the trend of cost of the rival fuels is expected to be roughly parallel. Over many years, however, the costs of solid fuel and electricity have steadily converged, and this tendency is likely to be accentuated in the future. It is often possible to show that the saving in capital costs effected by installing floor heating is sufficient to pay for all the electricity that is likely to be consumed over a period of some years, by which time electricity may be expected to be even more competitive than it is at present.

The reference to unsuitability of floor heating for halls occupied only occasionally does not presumably refer to churches. There are numerous installations in churches which appear to be giving every satisfaction, and many more are being provided. An essential factor would seem to be the reduction of the thermal inertia to ensure that effective heating at floor level is available fairly quickly.

It is desirable that as many dwellings as possible should be equipped with floor heating now, as a house once built will last perhaps 60 years, and it is difficult to install heating of this type once the structure has been completed. Within the anticipated life of the dwelling, nuclear generation is expected on a large scale, and solid fuel may be expected to become ever more costly. Off-peak tariffs are, in general, not attractive to the domestic consumer at present, and unless attention is paid to this now, we may find difficulty in the years to come in attaining the balance which we desire between the day and night load.

Mr. T. Duerden: Reference has been made to church heating by means of a quick-response floor, where the heating cables are embedded in a thin screed laid on heat-insulating material, and also to the construction of an intermediate floor where the screen with the heating cables was laid on top of a layer of Fibreglass.

I have had experience of a garage floor, where, because of the high water table, a layer of Vermiculite concrete was laid immediately below the screed containing the heating cables. The floor was divided by expansion joints into squares of about 9 ft side. When heat was applied these squares 'dished', and the passage of the traffic over them cracked the concrete in the corners of the squares.

Have the authors had similar difficulty owing to thin screeds not adhering to the heat-insulating layer, and what type of heat insulation do they recommend for use in the quick-response floors of churches?

Mr. R. A. H. Livett: With regard to the problems of insulating the walls and floors of blocks of flats against airborne and impact noise, I would lay particular emphasis on the importance of the floor. Has any experimental work been done by those responsible for promoting electrical floor warming, with a view to satisfying themselves that a floor designed to give the maximum degree of insulation is suitable for the installing of electric floor-warming equipment?

Mr. W. Cameron: Electrical floor warming provides a very comfortable form of heating, spreading comfort over the entire floor area and providing the heat in the places where it has the most value, i.e. at floor level. It also provides a very nicely balanced mixture of radiant and convection heating, and thus more closely balances the heat lost from the human frame than does air warming.

The paper seems to confine the use of directly-buried heating elements to one or two small domestic buildings, but perhaps this may be affected by the scope of the paper, which is limited to the experience in south-east Scotland. Overall, I have knowledge of some 760 heating installations which have been, or are being, completed at the present, with a loading approximating to 17 MW and using approximately a million yards of a mineral-insulated cable directly buried in the screed. Of these 760 installations we have exact records of 240 and these cover the following:

Churches and convents	26
Houses, flats and bungalows	66
Shops, offices and stores	68
Factories and garages (one factory loaded at approximately 3 MW)	49
Schools	12
Libraries	5
Power stations, control rooms and switching stations	5
Cafés and public houses	3
Hospitals	3
Banks	3

I agree with the authors on the question of electrical space heating against solid-fuel systems, and would mention one instance of a church, in which, during the 18 weeks' drying-out period, the electricity consumption came to £60. A sister church of exactly the same design in another district cost £147 for coke firing. This amount, not taking into account the wages of a caretaker or for extra cleaning or ash removal, etc., shows that the figures given in the paper are generally in favour of electrical floor warming as against solid-fuel or oil-fired systems.

In buildings such as offices and hotels, decorating costs can be greatly reduced when using space heating as distinct from conventional heating methods. Another point in favour of floor heating is the absence of maintenance, pipe fitting, boiler cleaning, chimney sweeping, caretakers' salaries, etc. There is no risk of pipes bursting or freezing as often occurs with hot-water systems.

With regard to Mr. Livett's question about impact noise on concrete floors, I believe the authors found that, where the heated

screed was fully insulated from the sub-floors, no complaints had arisen about noise from upper floors. Does this fully insulated heated raft, floating on the sub-floor, not detract from the system of floor heating by using the bulk of concrete as storage, and would it not allow quick response, quick loss, and a longer running period to enable a continuous temperature to be reached, which is the basis and virtue of what one might term bulk heat storage?

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSIONS

Mr. E. Bates (*in reply*): The breadth of discussion on the subject indicates the considerable interest taken in it, and it is gratifying that this is by no means restricted to those whose views could be biased by commercial interests.

Most contributors agree first that each installation should be properly and carefully planned, and secondly on the importance of automatic control.

The need for careful planning is acknowledged, but the situation must be faced that, with the growth of popularity of this method of heating, installations will be carried out more and more by persons unable or unwilling to apply careful planning; and if some 'rule of thumb' methods can be devised which, if anything, tend to over-equip installations, the harm that can be done by unplanned installations might be minimized.

Some doubt has been expressed as to the adequacy of available means of automatic control to avoid the waste of energy or discomfort conditions. In this connection, there appears to be an expectation of rapidly-changing temperature conditions which, in my experience, very seldom occur. In fact, the only real difficulty has been in rooms fitted with large windows exposed to direct sunlight such that at the beginning and end of the heating season the solar gain could be considerable on bright days. During the hour or two in which such conditions can obtain, extra ventilation appears to be necessary although this does not result in a serious waste of heat, because, as one speaker comments, the rising ambient temperature naturally reduces the rate of output from the storage heater.

After experiencing the different forms of automatic control that are available, I am of the opinion that those related to outdoor temperature are the most reliable (provided, of course, that the installation is itself adequate and that the controls are properly set), and I should like to see some practical results from the use of the modified form of outdoor control put forward by Mr. Rowson, which introduce a refinement. In this case care would have to be exercised to ensure that the setting of the manually controlled resistors was accurate and not open to abuse by occupiers of rooms.

It was with some hesitancy that I quoted in the paper any figures of annual consumption, because these can be affected by so many conditions, and, in any case, to express the consumption in terms of kilowatt-hours per kilowatt installed is clearly open to error because of the empirical method of arriving at heat losses to determine installed loadings. It would appear that the only satisfactory way in which to compare the costs of heating by different methods is to relate the kilowatt-hour consumption per unit cube of heated space to the degree-days temperature rise provided. To do this requires the compilation of correct records, which are not easily obtainable under practical conditions in consumers' premises.

There is a real possibility of fires being caused by heaters masked by inflammable material, and this must be guarded against. First, the risk will be inherently smaller if the loadings of heaters are kept within limits such that, when freely exposed, a steady temperature state under conditions of continuous charging does not itself exceed a dangerous level; in locations where there are masses of non-conducting inflammable material, e.g. bolts of cloth, either this form of heating should not be recommended or, alternatively, suitable guarding should be applied so that the materials cannot come in direct contact with the faces or top of the heater; the use of temperature-operated safety cut-outs will help under certain circumstances.

Mr. Mills is wise to draw attention to this matter, although it is hoped that, when the characteristics of this form of heater become better known to users, care will be taken to avoid accident. I believe that, in every accident which has so far occurred, either the user has rendered the control gear ineffective, thus creating excessive temperatures, or, alternatively, carelessness in permitting the heaters to become masked with material has been the cause.

It is agreed that the charges for electricity consumed at off-peak hours are, at present, not substantially above the cost, but even at this level they are contributing to certain overhead charges that would otherwise have to be borne by on-peak charges. It is considered, however, that the monetary level of these off-peak charges is satisfactory, and it is expected that, as time goes on, the differential between the off-peak and on-peak charges will become wider, which will thus encourage the transfer of demand to night-time.

Of course, ventilation is almost inseparable from heating; but in planning a thermal-storage heating installation regard will be had to the desired rate of air change during the occupied period, and this will affect the load to be installed. Ventilation should, however, be reduced as nearly as possible to zero during the unoccupied hours, in order to discourage the rapid discharge of heat and to ensure that as much as possible of that liberated will be stored in the fabric of the building and its contents.

There is the special problem of heating rooms having unusually long hours of use, such as classrooms where evening classes take place. Consideration can then be given to the use of a midday boost, although, in practice, it has been found that the drop in temperature in the evenings is relatively small, most likely owing to an increase in occupational gains during the evening when the rooms are fully occupied by scholars and when artificial lighting is in use. Another problem is the heating of rooms that are used only in the evenings, e.g. the village hall. An attempt is being made to design a heater embodying some manual means of restricting the liberation of heat until occupation of the room demands it, whilst, at the same time, avoiding the exposure of high-temperature surfaces which would result from the application of additional removable surface insulation.

Messrs. J. W. Moule and **W. M. Stevenson** (*in reply*): We were most impressed with the great interest shown in the paper, and regret that space is insufficient to permit a full reply to the many points that have been raised. In particular we were pleased that Mr. Bernard could open the London discussion in view of the fact that, when Mr. Grierson's paper[1] was read before The Institution in 1941, Mr. Bernard made the prophetic utterance, 'I feel that there will be considerable scope for the use of the floor warming method of heating in various kinds of building in the future because it is so effective and so efficient.'

A fundamental point raised by Messrs. Dale, Wilson, Ballamy, and Cundall is whether electrical off-peak space heating is in the best interests of fuel conservation. This point has been raised on many occasions, and it is answered in the Introduction to the paper. In brief, the development of off-peak load is essential both to enable modern coal-fired stations to operate at the highest possible thermal efficiency and to provide an outlet for nuclear-generated electricity which might otherwise be wasted.

The questioners also seem to have forgotten that the modern coal-fired generating station burns fuel of an inferior quality, and the change-over of heating systems to off-peak electricity thereby enables a much better quality coal to be released for other uses. Messrs. Bernard and Barlow emphasize the importance of developing off-peak load, and we agree with the views they express.

Several speakers question the ability of electrical floor warming to deal successfully with sudden changes in ambient temperature and suggest that there would be an excessive waste of electricity on a relatively warm day. Mr. Bruce is critical on this account, but Messrs. Bernard and Taylor appreciate the fact that, owing to the low temperature at which heat is stored, the electrically warmed floor is, to a large extent, self regulating. This point is dealt with in the first paragraph of Section 4.4.

Miss Griffith and Messrs. Shepherd, Adcock and Wilson refer to the calculation of the electrical loading of a floor-warming installation. Several of these speakers were in difficulty over Table 1, and it should be explained that the average temperature rise referred to there relates to the occupied spaces in the building. Corridors, halls, etc., have a smaller temperature rise, and, in relating building heat loss to the electrical loading, regard must be paid to the variations of design temperature rise in the various parts of the building. It was, of course, impossible to include all these details in Table 1. Our experience is that the installed loading shown is more than sufficient to maintain the desired comfort conditions even in the coldest of weather.

Associated with the calculation of kilowatt loading, is the ascertainment of annual electricity consumption. Miss Griffith refers to cases where the actual consumption is much less than the estimated value. The figures given in the paper, and indeed in further results obtained since the paper was published, show that, in general, the actual performance of the floor-heating installations is appreciably better than the estimates based on the calculated heat loss.

Inevitably some building construction problems were raised during the discussions. Messrs. Bernard, Lennox, and Parker refer to the possibility of cracking in the screed owing to lack of proper cohesion between it and the structural floor. This is essentially a builder's problem, and where proper care is taken, both in the laying and in the mixing of the screed, no trouble should arise. Unfortunately, the existence of a floor-warming installation sometimes provides a ready excuse for the builder, even though the screed would have cracked in any event owing to poor workmanship. An associated question relates to thermal insulation of the building. We agree entirely with Messrs. Bernard, Livett, and Cameron on the need for proper thermal insulation. It would be wrong, however, to create an impression that the cost is a charge against electrical floor warming, as good thermal insulation is a necessity for any heated building.

The Kirkcaldy electrically-floor-heated flats were referred to by a number of speakers. Messrs. Bruce and Jamieson use this installation as an argument that electrical floor warming should be confined to the provision of background warmth. Mr. Barlow is also of this view. We agree that there is something to be said for this in the living-room of domestic premises, where the occupiers wish to use a coal or coal-effect electric fire, apparently for psychological reasons. It should be emphasized, however, that in the case of larger buildings, including most of those referred to in Table 1, off-peak electrical floor warming provides the whole of the required space heating at reasonable cost. In view of Mr. Jamieson's remarks about Miss Griffith's paper,[2] it should be pointed out that this experimental installation was installed in a temporary building with poor insulation. Fig. 6 of our paper shows that the variation in internal temperature is quite small.

On the design of floor-heating installations, Mr. Barlow prefers the withdrawable system, but, as Mr. Greer points out, it is much more costly to install. We feel that Mr. Barlow takes too pessimistic a view of the incidence and cost of repairs to faults in solidly embedded systems. With regard to the use of a D-shaped cable housing rather than a simple tube system, we understand the flat surface of the D-shaped housing is claimed to provide better thermal contact with the heat diffuser than would be possible with a tube. Mr. Gilchrist questions the necessity for a heat diffuser, and we feel he is going too far in stating that it has been proved conclusively that it does not improve heat distribution over the surface of the concrete. Our experience is that a heat diffuser is of considerable advantage, not only for its main purpose, but also in that it provides reinforcement for the concrete screed. His fear about the deterioration of metal housings seems to be groundless, as it would be possible to replace heating cables in the concrete passages even if the surrounding metal had been the subject of chemical attack.

Messrs. Bernard and Gilchrist support our view on the satisfaction provided by electrical floor warming, and Mr. Barlow brings out the important point that its installation leads to a reduction in the cost of decoration. This is a material factor which is often overlooked, owing to the difficulty of placing a monetary value on it.

We are surprised that Mr. Dale does not like the comparison shown in Table 2. Our experience is that heating engineers and their clients welcome the opportunity of drawing up a comparison of heating costs which take all relevant considerations into account. The sickness rate at St. Mungo's School is low having regard to experience at other schools in the area.

Mr. Schiller expresses certain fears, which, we can assure him, are quite groundless. Tests of the a.d.m.d. at Kirkcaldy bring out a figure of 3·98 kW per dwelling as compared with his estimate of 5 kW. This was on 25th December, 1956.

We are indebted to Dr. Marmorek and Mr. Sadler for providing details of the floor-heating installations in which they are interested, and it is encouraging to receive the expression of appreciation from the workers employed in Mr. Sadler's building.

DISCUSSION ON

'SOME ASPECTS OF HEAT PUMP OPERATION IN GREAT BRITAIN'*

SOUTHERN CENTRE, AT BRIGHTON, 13TH MARCH, 1957

Mr. H. H. Lawrence: For the last two years I and my colleagues have been working on the construction and operation of a small heat pump which is heating a greenhouse at Eastbourne.

I believe that there is an urgent requirement for the design of plant ranging in size from 10 kW to more than 100 kW of output capacity.

I will confine most of my remarks to the smaller sizes of plant, such as those which might be suitable for, and have application to, small commercial undertakings and horticulture. In this category, immediate attention should be given to the production of a hermetically sealed unit. These plants cannot include as many ancillaries as are shown in Fig. 1, and in my own application I have buried the evaporator carrying the Arcton charge directly in the soil to a depth of 24 in, which is satisfactory. The frost line does not penetrate more than 22 in below the evaporator or at a greater distance than 15 in to one side of the pipework in the soil, and the temperature gradient is as much as $\frac{1}{2}°$ F per inch. I have noted that the recovery of the soil temperature appears to be more rapid than the results indicated in Fig. 3. This may be due to the shallow depth at which the pipes are placed and because on the south coast we are fortunate in having long periods of sunshine during the winter.

If we examine Table 4 and recast it for a 10 kW output we find that the figures are more in favour of the heat pump, as the cost for attendance of a solid-fuel boiler does not reduce very much for the smaller output, and becomes a greater proportion of the total operating costs for solid fuel. The capital cost of a solid-fuel boiler plant having an output equal to 10 kW would be £150, and I am hoping that we can design and install a heat pump for a figure which will not exceed £500. The running cost of the solid-fuel boiler would be of the order of £110 per annum, as against £103 for the heat pump. It certainly appears very necessary to stress that proper account be taken of attendance, maintenance and amenity charges when making a comparison with the cost of solid fuel.

That much progress has been made in America with practical applications is all too frequently dismissed by saying that the dual-purpose application of heating and air conditioning makes operation economic in that country. From this we are left to infer that the proposition is not worth considering in this country. I do not agree with this, since, even when used only for heating and with the relatively low performance energy ratio of 3, the heat pump has a place in this country in the immediate future if certain basic requirements can be met. These are as follows:

(i) A manufacturer with the necessary resources should produce a standard 'packaged' plant of, say, 10 kW output rating which has a hermetically sealed unit.

(ii) The design and method of installation must be simple and require the minimum number of parts to be assembled *in situ*.

(iii) If hot water is to be the medium used for heat distribution, adequate storage capacity is necessary to allow for off-peak operation on the most favourable tariffs.

The greatly accelerated nuclear power projects should not weigh too heavily against the heat pump. We are told that, even by 1975, the nuclear power stations will only be keeping pace with the increase in electrical power requirements and that the steam stations will still require as much coal from the mines as they do at present. This is surely a very strong reason for the heat pump to be regarded as a means whereby the fuel resources in this country can be conserved.

The paper sets limits within which commercial development of the heat pump can proceed and supplies the answers to a number of previously unknown quantities affecting design. I hope that manufacturers will study the work which has been done and provide suitable plant which supply engineers can sell with complete confidence.

Miss M. V. Griffith (*in reply*): Mr. Lawrence points out the urgent requirement for larger sizes of hermetic units than are, at present, available. It is possible that such units will be available in the not too distant future, since one major refrigeration firm is steadily bringing out models of ever-increasing capacity.

It is, of course, preferable, from the point of view of heat transfer, to bury the evaporator itself in the soil, but in units of any size joints must be made in the pipes, and there is then a leakage hazard. Mr. Lawrence does not say how far upward his frost line travels. The reason for burying pipes at least 3 ft down in the soil is the fact that plants draw their water from depths down to 2 ft, and it is, in general, undesirable to freeze above this level.

I presume that the figure of £500 for an installed heat pump with an output of 10 kW includes the cost of an earth source, since it should be easy to keep to this figure or even well below for an air source. I agree with the three conditions laid down by Mr. Lawrence, but would point out that these are being met to a great extent by prototypes not yet commercially available because of the inhibiting effect of purchase tax. It is encouraging to note that supply engineers consider that the heat pump could be sold with confidence in this country.

* GRIFFITH, Miss M. V.: Paper No. 2273 U, December, 1956 (see 104 A, p. 262).

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ELECTRICAL PROCESS HEATING

A Review of Progress

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(1) INTRODUCTION

The subject of process heating was included in an earlier review on electrothermal, electrolytic and electrostatic processes and welding;[1] this review also dealt with the melting of metals—a branch of process heating which is not covered in detail in the present one. Earlier references to process heating were also made in the review of the application of electricity in factories.[2] The present review covers the low- and high-temperature treatment of metals and such non-metals as plastics, rubber, wood, ceramics and glass. There are indeed few products which are not heated at some time during manufacture, and it will be clear that within the space available only brief mention can be made of the features of some of the processes.

During the past few years there has been a general trend in heating, as in many other industrial processes, towards higher productivity and economy in the use of fuel. The need to make the best use of the national fuel resources and of the available labour force has influenced the development of heating processes and encouraged the use of electrical heating. New methods of heating have become established in traditional industries, and considerable improvements in economy, productivity and working conditions have resulted from the changes which have been introduced.

The industrial consumption of electricity supplied by the C.E.A. has increased from about 23 × 10⁶ MWh in 1950–51[3] to over 31 × 10⁶ MWh in 1955–56[4]—more than half the total sales of electricity. In addition, some industries generate their own electricity, and part of this is used for heating processes.

During the period under review the Ridley Committee reported on the national fuel resources and on industrial and commercial fuel consumption.[5] The Committee recorded that the quantity of fuel used for various industrial purposes was not known, but estimated that motive power may account for one-quarter of industrial fuel consumption and attributed the rest mainly to process heating and factory space-warming. Fuel-consumption statistics have been published[6] for particular industries, such as iron and steel, and the consumption in some other industries, including the non-ferrous-metals industries, is known[7] from other sources.

Table 1 shows the consumption of various fuels in the metal-treatment industries in 1950, and it is apparent that the use of electricity in these industries was substantial when compared with the use of other fuels; moreover, it comprised about 60% of the total amount of electricity used in industry as a whole. It can be shown from Table 1 that the ratio of the coal equivalent of the electricity purchased to the coal purchased is approximately 1 : 3 for the iron and steel industry and 1 : 1 for both the non-ferrous metals and the engineering industries.

The actual quantities of electricity used for various purposes in each industry could only be estimated from general experience of current practice. In the non-ferrous industries a good guide can be obtained from figures published by Ashen for a representative group of works.[8] The proportion of the load supplied by electricity, both purchased from outside and generated in the works, is fairly high, being approximately 60% on an equivalent-coal basis, and the energy used for melting and annealing is 30% of the total used in the works. The electricity consumed by some industries is known from sources other than the Census of Production. In the pottery industry, for example, where the bulk of the production is located in one area, the consumption of electricity for firing has been recorded by the Midlands Electricity Board.[9] The results of a survey published in 1954[10] showed that about 10% of all the ware produced in North Staffordshire was fired by electricity, and since 1953 the use of electricity in the Potteries has increased by nearly 15%. It will thus be clear that it is impossible to treat the various branches of process heating in an order of importance based on the quantity of electricity consumed, although the metal-treating industries must rank high.

In many industries the cost of fuel for processing is only a small fraction of the cost of the material being processed and therefore of the final product. In these industries an important consideration is the avoidance of loss and spoilage of material during processing, and the use of electricity is common. Now, as in the past, the principal factor in determining which type of equipment or which fuel shall be used is the need for financial economy and not concern for economy in the use of primary fuel. During recent years, although the cost of all fuels has increased substantially, the relative increase for some uses has been much less for electricity than for other fuels,[11] and the balance of costs is changing in a way which will encourage the use of more electricity. In consequence, the financial economy in changing over to the use of electricity is becoming an increasingly important factor.

During the period under review the Third International Congress on Electroheat has been held, and several joint papers were presented on behalf of groups of British manufacturers of process-heating equipment. These will be referred to further under separate headings in this review.

(2) SOURCES OF HEAT AND POWER

Most ovens and furnaces used for process heating depend on the use of resistance materials in which the heat is generated and from which heat energy is transferred to the work. In some processes the heat is induced directly in the work, and many such processes depend on power generators which operate at frequencies above that of the normal power-supply system.

(2.1) High-Temperature Resistance Materials for Use in Air

The majority of resistance ovens and furnaces are used for the heat treatment of materials and components at temperatures below 1100°C, and nickel-chromium and nickel-chromium-iron remain the resistance alloys most commonly used for these. Recent improvements in materials enable higher operating temperatures to be used, and greater heating rates are consequently obtainable. An upper temperature limit of 1150°C is usual for the nickel-chromium alloy which is basically of 80/20 composition, and one of 1050°C for the nickel-chromium-iron alloy of

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Table 1

APPROXIMATE QUANTITIES OF FUELS USED FOR METAL TREATMENT IN 1950

(Including some figures from 1948 Census of Production)

Industry	Coal	Coke	Gas	Fuel oil for burning	Creosote pitch	Electricity	
						Public	Works generated
	tons $\times 10^3$	tons $\times 10^3$	therms $\times 10^3$	tons $\times 10^3$	tons $\times 10^3$	MWh $\times 10^3$	MWh $\times 10^3$
Blast furnaces	—	10 130(*b*)	—	—	—	—	—
Iron and steel(*d*)	8 340(*a*)	1 350(*b*)	—	936(*e*)	233(*e*)	3 600	1 300
Engineering or engineering and shipbuilding	3 770(*a*)	890(*b*)	—	404(*e*)	32(*e*)	6 000	400
Non-ferrous metals	630(*c*)	240(*c*)	—	—	—	900	200
Totals	12 740	12 610	—	1 340	265	10 500	1 900
Total industrial(*g*)	45 880	15 080	589 642(*f*)	2 145	519	20 400	—
Total as percentage of industrial	28	84	—	62	51	61	—

(*a*) Taken from Table 73, Ministry of Fuel and Power Statistical Digest, 1950.
(*b*) Taken from Table 135, Ministry of Fuel and Power Statistical Digest, 1950.
(*c*) Taken from 1948 Census of Production.
(*d*) Excluding tinplate.
(*e*) Taken from Table 156, Ministry of Fuel and Power Statistical Digest, 1950.
(*f*) Includes coke-oven gas, taken from Gas Council Report, paragraph 205. Allocations to separate industries not known.
(*g*) Excluding gas, electricity, water, railways, coke ovens and collieries.

65/15/20 composition. Other resistance materials are used for higher temperatures. A nickel-chromium-aluminium alloy recently introduced is claimed to have better oxidation resistance than the 80/20 nickel-chromium alloy in the range 1100–1 250° C, and it is being used in some high-temperature furnaces, such as those for firing pottery.[12] For the range 1 200–1 350° C the chromium-aluminium-iron alloy (Kanthal) of 23/6/69 composition shows superior oxidation resistance, but because it becomes brittle after a short time in service, special precautions must be taken in supporting and mounting the elements. It is commonly used in pottery furnaces.

Silicon-carbide elements continue to be used up to 1 400° C, but are brittle and increase in resistance throughout their life; it is usual to connect them to a continuously-variable or stepped voltage supply, so that the initial loading can be maintained. A method of compensating for the resistance change, which may be as high as 4 : 1, by the use of static equipment has been described;[13] this involves connecting reactances in series with the heating elements and results in the variation in power level being reduced to only a few per cent. An improved type of silicon-carbide element introduced within the last few years consists of a one-piece tube having a central hot zone in the form of a spiral cut in the tube. It is claimed to be suitable for operation up to 1 575° C and to have much improved ageing characteristics, the increase in resistance taking place much more slowly than with the other silicon-carbide elements.

Great interest always centres on heating elements which will operate satisfactorily in air at temperatures above those for which the chromium-iron-aluminium and silicon-carbide materials are suitable, and there have been many such developments in recent years. Some of the attempts to produce high-temperature elements have achieved only limited success, but others have been more successful and units are operating in production. Much useful information has been presented on the properties of high-temperature materials and their use in furnaces.[14] Tungsten and molybdenum elements protected from oxidation by ceramic coatings have been tried, but are not yet widely used. The protection of molybdenum filaments by coatings of silicon, obtained by a gaseous diffusion process, have been tried and good oxidation resistance at temperatures up to 1 700° C is claimed.[15] A recent innovation is an element based on molybdenum which is claimed to operate up to 1 700° C without a protective atmosphere. Elements of this type are prepared from molybdenum disilicide powder by hot pressing, or by extrusion and sintering,[16] but as yet are available only in small pieces. Other trials have included the use of refractory oxides, such as zirconia, but the necessity of preheating the oxide to a fairly high temperature to make it conducting leads to complications.[17] Elements of molten glass contained in refractory channels are in use on a commercial scale for heating metals to about 1 250° C.[18] Electricity is conducted to the glass through graphite electrodes, and water cooling near the electrodes ensures that a seal of solid glass is maintained around them.[19]

(2.2) High-Temperature Resistance Materials for Use in Gas Atmospheres and in Vacuum

Many of the furnaces in which nickel-chromium and nickel-chromium-iron resistance alloys are used have special atmospheres, introduced to prevent deterioration of the product by oxidation or to produce some desired change in the product, such as in carburizing and nitriding. Although most atmospheres have no adverse effect on the oxidation resistance of the heating elements, there are some atmospheres in which 'green rot' can take place and premature failure result. This problem has been dealt with in different ways. Alternative alloys containing nickel, chromium, iron and silicon, which are less susceptible to this form of hot corrosion, have been developed and are used when the deterioration cannot be avoided by adjustment of the furnace atmosphere. Additions of up to 1·5% silicon are also made to the 80/20 and 65/15 alloys to give enhanced corrosion resistance. Another way of avoiding this difficulty is to protect the resistance element from the atmosphere by enclosing it in a tube of heat-resisting alloy. This so-called 'electric radiant tube' has some advantages and its use is increasing. The sheath material can be chosen so that the corrosion by the furnace atmosphere is minimized and deterioration of the sheath does not affect the electrical characteristics of the element. The outer tube also protects the element against mechanical damage, and the sheathed element is so arranged that the resistance wire can be replaced without requiring that the furnace be shut down. A disadvantage, however, is that the element operates at a comparatively high temperature and its life is consequently reduced.

For temperatures between 1400 and 1700°C small furnaces wound with molybdenum heaters are becoming increasingly used.[20] Molybdenum elements must be protected by an atmosphere such as dry hydrogen, and provision must be made to vary the supply voltage to compensate for the large increase in resistance as the elements become hot

Graphite has long been used for high-temperature elements in both resistance and induction furnaces for special purposes. It is relatively cheap, has satisfactory mechanical properties up to 2600°C and has a substantially constant resistance over a wide range of operating temperatures. Furnaces using single-phase elements have been used, for the treatment of small parts in vacuum.[21,22] For the high-temperature heat treatment of graphite and some metals a furnace using a 3-phase element has also been designed, and the use of larger furnaces of this type is increasing.[23]

(2.3) Embedded Elements and Radiant Lamps

The metallic-resistance materials described in the previous Sections are usually wound on rods or tubes of refractory material, or are supported directly from the refractory lining of the furnaces. The elements are generally exposed and are free to radiate to the surroundings.

Sheathed elements made by embedding the resistance wire in a refractory insulation—usually magnesium oxide—inside a metal tube are being used on an increasing scale. The method of manufacture varies, but sheathed wire elements are available in diameters from about ¼ to 1 in and in lengths up to about 20 ft. The loading densities vary over a wide range, depending on the application, being about 5–10 watts/in^2 for oil heating and 50–60 watts/in^2 for water heating. Sheath materials such as mild steel, copper, brass and heat-resisting alloys are commonly used. The elements can be bent into various shapes, and can also be cast into lead and aluminium blocks. A common use of these elements has been for heating water and oil, but they are being used to an increasing extent for heating ovens, platens, dies, salt baths, solder and tin baths and for many special purposes.[24,25]

Sheathed wire elements mounted in reflecting troughs are finding increasing usage as radiant-heating units. The radiant troughs, each having a loading of about 3 kW and provided with bright metal sheets to act as reflectors and to exclude draughts, can be assembled to make ovens of different sections. Radiant ovens are used for process temperatures up to about 300°C, and are not usually provided with thermal insulation. The loading density is about 1 kW/ft^2, but some sheathed-wire-element panels having twice this loading are used for special purposes. Ovens of this type are controlled mainly by regulation of the input power, and repeatable temperatures are obtained by accurate control of the heating time or speed of transfer through the oven. In some of the ovens used for heating thermoplastic materials, electrical switching enables a steady temperature to be maintained, after the preheating, until the material is withdrawn from the oven.

The sheathed-wire-element radiant trough has to a large extent displaced that in which tungsten-filament lamps are used. Lamps are retained for some special applications, and the 250-watt lamp with the reflecting surface sprayed on the inside of the bulb gives loading densities approximately the same as those of the sheathed-wire-element troughs. More recently, tubular tungsten-filament lamps have become available, and their use for special purposes is being explored. High loading densities can be obtained with the 1 kW quartz-tube lamps, which are 10 in long and ½ in in diameter.

Heaters made of woven heater wire and heat-resisting fabric are used for low-temperature applications up to 200°C, and a flexible heating 'mat' made by facing conducting rubber with insulating rubber is reported to be widely used in America for some wood manufacturing processes.[26]

A recent development is a type of element which, together with its insulation, is applied to surfaces by a spraying process. This has been developed for de-icing the surfaces of aircraft, but it is applicable to other structures, particularly where the surface to be heated is of complex shape.[27]

(2.4) Conduction and Induction Heaters

(2.4.1) Mains-Frequency Heaters.

There are many low-temperature applications of heaters in which the heat is not only developed in the element by conduction loss but it is transmitted to the material being heated by thermal conduction, e.g. the use of steel strips connected to a low-voltage supply to heat wood assemblies. The conduction heating of steel vessels and pipes and of some engineering components has increased. Design details for the heating of mild-steel pipes to temperatures below the Curie point have been published,[28] and the method is being used for the heating of liquids during transfer.

There has been marked progress in recent years in both mains-frequency and high-frequency furnaces for melting and heat-treating metals. Although melting is beyond the scope of this review, it is of interest to note that progress has been made in extending the use of cored-type mains-frequency furnaces to the melting of metals other than brass and aluminium, for which they have been used for many years.[29]

Coreless mains-frequency furnaces are becoming of great interest and, apart from melting, are being used for both low- and high-temperature heating of metal. In essentials the furnaces are simple, for they consist of water-cooled copper coils surrounding the body to be heated, power-factor-correction capacitors and control equipment. Power is supplied from low-voltage transformers provided with tappings for adjusting the voltage, and furnaces of this kind having input powers of up to 350 kW are in use. The standby losses are zero, the thermal losses are low and the furnaces are readily controlled by automatic means.

(2.4.2) High-Frequency Alternators.

Many induction-heating applications require sources of power at frequencies higher than the mains supply, and alternators are used for those which involve the treatment of large masses, and therefore require large powers. In the frequency range 1–3 kc/s generators having output powers of up to about 1 MW are available, and at higher frequencies 10 kc/s machines rated up to 300 kW are in use for heat treatment. Recent improvements have been in detail rather than basic design, and there is a trend towards closed-circuit cooling. Alternators are usually housed in a separate substation, and power-factor-correction capacitors, control gear and water-cooled induction-heating coils complete the equipment.

(2.4.3) Valve Generators for Induction Heating.

Valve generators[30] are now available in sizes up to 200 kW, although for the majority of applications, powers up to about 30 kW are more commonly used and operating frequencies are in the region of 500 kc/s. Recent trends have been towards simplifying the generators, making them more compact and providing variable-output circuits. Variable-output transformers enable optimum heating conditions to be achieved for a variety of applications, and the power output may be adjusted during the heating cycle. The method of rating valve generators has now been standardized.[31] Both air- and water-cooled oscillator valves are used, and in some recently designed generators other types of rectifier have taken the place of the mercury-vapour

unit. Accurate repetition of most cyclic heat treatments is ensured by control of the power output from the generator and of the duration of the treatment, rather than by temperature control.

(2.5) Dielectric Heating Generators

Valve oscillators for dielectric heating are generally similar to those used for induction heating, but the operating frequencies are higher. The largest generator reported[25] has an output power of 140 kW and a frequency of 10 Mc/s, but smaller generators for plastic work operate up to 60 Mc/s. For some applications the electrodes are built into ovens or presses which form an integral part of the generator. For others, the electrodes are built into jigs and fixtures which may be remote from the generator and connected to it by feeders and variable matching units.

Continuous-wave magnetrons operating at about 1 000 Mc/s are used in commercial heaters in America, and valves having output powers of 5 kW have been reported.[32] In Britain, generators of this type have so far been used only for experimental work. The heating can vary from a maximum to nearly zero within the space of many articles to be heated unless special techniques are used.

(3) RESISTANCE FURNACE PROCESSES

(3.1) Metal Treatment

There have been a number of reviews of electric furnaces in the past few years, and summary reports[33–36] of furnace installations have been made at intervals.

(3.1.1) Treatment of Ferrous Metals.

Until recently, electric furnaces have been little used to reheat steel prior to hot working, because of the higher cost and the difficulty of providing resistance elements with a sufficiently high temperature range. The new type of furnace using molten-glass resistance elements is now being used to heat billets and ingots prior to extrusion and forging.[19]

Although the use of open batch-type electric furnaces to heat forgings, castings and bar stock continues to increase, probably the greatest expansion has been made in the use of controlled-atmosphere furnaces. Bell-type and pit-type furnaces are used for the bright annealing of sheet steel, coil strip and wire, and here the improvements have been in detail rather than general design. High-speed fans are now commonly used to ensure rapid and uniform heating. Furnaces for bright annealing steel strip, decarburizing silicon-iron strip, nitriding and other heat treatments, such as the malleableizing of castings, have become standard equipment, and electric furnaces are used in preference to those fired by other means because of the accurate control, cleanliness and—in most cases—economy they offer.

For the surface hardening of steel components gas carburizing is displacing the old pack-carburizing methods, and both batch and continuous furnaces are used for this process; the atmosphere which surrounds the charge during heating and cooling is derived from propane, butane, town gas or from organic liquids.

Carbonitriding—a surface-hardening process similar to carburizing, but with ammonia added to the atmosphere of the carburizing furnace—is becoming more widely used. It is most suitable for obtaining shallow case hardening which might otherwise be obtained by treatment in salt baths, and surface cases containing amounts of both nitrogen and carbon are produced. Full case hardness can be achieved with oil quenching, and this, coupled with the lower treatment temperature, tends to cause less distortion. Both batch and continuous furnaces are now being used for carbonitriding and in these the quench tank is an integral part of the equipment and is protected by an atmosphere.[37]

The copper brazing of stainless-steel parts in an atmosphere of dry hydrogen is carried out in pit-type furnaces. With the introduction of special steels and alloys for operation at high temperatures in modern engines, the need for new methods of fabrication has grown and is being met by the use of high-temperature brazing.[38] An essential requirement of this process is a rapid rate of heating, and graphite-resistance furnaces are being used. Fluxless brazing of Nimonic 90 alloys can be achieved in such a furnace.

Salt baths are commonly used for the treatment of tool steels, especially when high-speed production requires the baths to be operated continuously. A range of baths operating at different temperatures is used for preheating, heating to hardening temperature and quenching. Heating of the baths by electrodes is common, particularly in the high-temperature range. For smaller outputs, where intermittent operation is adequate, resistance furnaces are preferred. Salt baths are also being used to descale stainless-steel parts, and this method avoids the pitting and embrittlement which can occur when the cleaning is done by acid pickling. Salt baths for this process are heated by either electrodes or immersion heaters.

(3.1.2) Treatment of Non-Ferrous Metals.

Electric furnaces continue to be used for almost all treatments of light alloys. They are also used for the treatment of copper, nickel and their alloys, but in this field the use of other fuels is common.[35,39]

The temperatures required for the heat treatment of aluminium are in the range 150° C–600° C, and forced-convection heating is commonly used. Large continuous furnaces, some having loadings of up to a few megawatts, are used to heat billets and slabs prior to rolling, and overall power consumptions of about 260 kWh/ton are claimed. Continuous-chain conveyor furnaces or pusher-shoe furnaces are favoured. In a recently installed roller-hearth furnace, billets are heated to 300° C prior to extrusion in a forced-convection oven of 165 kW maximum loading.[40] Horizontal forced-circulation furnaces are used for the solution treatment of extruded lengths of light alloy. The development trends have been in the direction of improving the rate and uniformity of heating and in providing heaters which are external to the furnace and are therefore more readily accessible for maintenance.

For annealing aluminium and aluminium-alloy sheets and products, both batch and continuous furnaces are used; the former are either horizontal or pit type, and both incorporate fans to improve the air circulation. The more recent developments in continuous furnaces are for rapidly annealing sheets for subsequent deep drawing. The sheets or blanks are placed singly on a conveyor instead of being stacked and the total heating and cooling time is of the order of a few minutes.

The use of electric furnaces for heating billets of copper and brass is still on a limited scale, but some rotary-hearth furnaces are used for this purpose. The use of controlled-atmosphere furnaces to anneal non-ferrous strip in coils has increased, however, and both continuous and batch furnaces are installed. For batch annealing both pit- and bell-type furnaces are used.

(3.2) Glass and Ceramics

In the glass industry most of the melting has been carried out in tanks and pots fired with fuels other than electricity, producer gas being fairly common, but more recently increasing interest has been shown in electric melting. An established use of electric ovens is for annealing glassware after blowing or moulding.

During the past ten years there has been a substantial increase in the use of electricity in the ceramic industry, mainly in the manufacture of pottery. Here, the cost of fuel is a comparatively

small fraction of the cost of the ware,[41] and the use of electricity has increased because of the accurate control, uniformity of heating and cleaner operation which it offers. Both intermittent and continuous kilns have been used for many years for some of the lower-temperature processes, but there has been an increase in the use of both types for pottery firing. Tunnel kilns are most suitable for the large-scale production of a standard range of ware, but the greatest expansion has taken place in the use of intermittent kilns because of their greater flexibility. The method of arranging the charge is much different in electric kilns from that used in kilns fired with other fuels. Another change brought about by the use of electric kilns is the considerable reduction in the firing time which has proved acceptable. Firing times of several days, necessary with fuel-fired kilns, have been reduced to a matter of hours.[42]

(3.2.1) Glass.

Fuel costs form a substantial proportion of the cost of melted glass, and in the absence of cheap electric power it has previously been concluded that electric melting would not be competitive; however, the change in the balance of fuel costs is now affecting this. In Britain more than 90% of the glass is melted in large tanks, which are kept in continuous operation, and the larger tanks have the highest efficiencies.[43] It has been proposed that electric heating could be used in the refining zone of the tank to boost the output of flame-heated furnaces by conducting a current through the glass between submerged electrodes. This method has been extensively developed in Europe, particularly in those countries having cheap hydro-electric power, and more recently all-electric furnaces have come into use for the production of high-quality glass.

It is well known that glasses become conducting at high temperatures, and for commonly produced types of glass the resistivity is of the order of a few ohm-centimetres at the working point. The change in resistance with temperature is large, and voltage regulation over a wide range is necessary to ensure satisfactory working; for example, the resistivity of soda-lime glass decreases from about 14 ohm-cm at 1 000° C to less than 5 ohm-cm at 1 300–1 400° C. Heat-resisting glass[44] has a higher resistivity, approximate values being 60 ohm-cm at 1 200° C and 30 ohm-cm at 1 450° C. Although the resistivity is fairly high, the cross-section of the conduction path for current is large and the voltage applied to electrodes placed in the glass is usually in the range of 50–100 volts. Both molybdenum and graphite electrodes have been used, but it is claimed that the latter have some advantages in producing glass free from 'seed'. The graphite electrodes can be up to several inches in diameter and require careful placing in the furnaces so that the distribution of current between the zones at different temperatures produces the required heating effect.

An electric glass-melting furnace has recently been developed in this country, and units are in production use for melting heat-resisting glass.[45] It is claimed that furnaces of this type have higher thermal efficiencies and lower initial and maintenance costs than those fired by other means; they are smaller, and having only a fraction of the refractory material needed in other melting tanks, they can be installed quickly.

(3.2.2) Ceramics.

The main use of electricity has been in the pottery-making branch of the ceramics industry, and it was recently estimated that 10% of the ware was fired by electricity in the North Staffordshire area; about 70% was fired in solid-fuel kilns and the bulk of all the fuel used was for biscuit firing.

Of the uses of electricity for the three main divisions of pottery treatment, namely biscuit firing, glost firing and decoration, the latter claimed earliest attention, partly because of the moderate temperature required—700–800° C—and it has become firmly established over many years; both batch and tunnel kilns were used for this purpose. Later, similar kilns were used for glost firing and for biscuit firing of earthenware at temperatures up to 1 100° C. Within the last few years continuous kilns for the firing of electrical porcelain and bone china, which require temperatures of 1 180–1 200° C, have been put into production use. Unlike the ware fired in solid-fuel kilns, that in electric kilns requires no protection from the atmosphere, and in consequence there are no saggars. The ware thus comprises a high proportion of the total weight of materials to be heated, particularly in some intermittent kilns, and the efficiency is thereby increased.

The growth in the use of electricity in the potteries during the last ten years is shown in Table 2. The large increase in the use of intermittent kilns in the last two years is remarkable. Many different types of kiln are now being used, including bogie hearth, rotary hearth and mesh belt conveyor.[46]

Table 2

Number of Electric Pottery Kilns and their Consumption in North Staffordshire Sub-Area of the Midlands Electricity Board 1946–56[9]

Year ended in March	Continuous kilns			Intermittent kilns	Consumption per year		
	Biscuit	Glost	Decorating		Decorating	Glost and biscuit	Total
					kWh	kWh	kWh
1946	—	4	26		6 482 819	4 529 194	11 012 013
1947	—	8	33		8 932 564	6 134 018	15 066 582
1948	—	19	33		11 576 618	11 957 881	23 534 499
1949	2	23	44		13 514 651	23 427 684	36 942 335
1950	2	30	46		15 070 000	30 550 000	45 620 000
1951	2	35	56		18 320 000	34 770 000	53 090 000
1952	2	39	62		21 725 000	38 567 000	60 292 000
1953	2	43	66		Not available		59 426 428
1954	3	46	64				63 981 228
1955	3	45	63	163			66 474 622
1956	3	44	63	225			67 841 280

(4) CONDUCTION AND INDUCTION HEATING PROCESSES

Power from the mains is being used for conduction and induction heating. In the former, steel strips connected to the

output side of low-voltage transformers are clamped directly in contact with parts to be heated, a typical low-temperature application being the heating of wood assemblies to speed the curing of the glue. Mains-frequency induction furnaces have been used for many years for melting brass: now, over 95% of the metal for hot working is produced in this way in Ajax-Wyatt furnaces, and large units loaded at 600 kW and producing at the rate of 2–3 tons of brass per hour are in use. A modified cored-type of furnace has also been adopted for melting aluminium, and recent progress in the refractories field has enabled nickel-silver, copper-nickel and other alloys to be melted in this way.[29] Coreless induction melting furnaces are being used for melting light-alloy scrap.[47]

Mains-frequency induction heating is becoming increasingly used for a variety of treatments as well as melting non-ferrous metals. In the low-temperature range, induction-heated rolls and press platens are being used, and recently the method has been developed for the induction heating of the transfer chambers in plastic moulding machines.[48]

Coreless inductors suitable for heating liquids in cylindrical metal containers have been designed,[49] and units with a mean rating of 150 kVA have a power factor of 0·6. Heat is generated in the walls of the vessel containing the liquid, so that the heater has a large surface area and the minimum thermal potential is required for quick heating. Furthermore, there is little surplus heat at the end of the heating cycle.

The rapid heating of billets of non-ferrous metals to the temperature required for rolling, pressing and extrusion is a further application of coreless induction furnaces. The method was first used in America for billets up to 1 ft in diameter, and its use is now spreading rapidly in Britain. The method is not efficient when used for billets much less than about 2 in in diameter.

Installations for heating large billets are in operation in this country. In one installation three 1 ft-diameter billets 5 ft long are heated to about 500° C, the rate of heating being such that one billet is withdrawn every 15 min. The input to the heater is 350 kW and the power factor of the inductor, 0·4, is corrected by capacitors. In another installation, 6 in-diameter billets are heated to 500° C in 4 min. Because of the rapid rate of heating achieved, a high output can be obtained with smaller equipment than is needed with the more conventional methods.[50] Machines for the successive heating of small billets of about 2 in diameter have been developed. The temperature of light-alloy billets is raised to about 500° C in 1 min, accurate temperature control ensures consistent results and automatic feed and ejection mechanisms give high output rates for the machine.

The method is not confined to the heating of non-ferrous metals. Steel can be heated[51] to the Curie point if the diameter is greater than about 1½ in. The method is generally efficient, because the standby power is zero and there are no weighty muffles or lagged enclosures to be heated.

Mains-frequency induction heating has also been used to relieve stresses in large structures, such as refinery pipes and power-station components which have to be welded on site.[52] Asbestos-covered cable is wound round the joint to be annealed and connected to low-voltage heavy-current transformers. Voltage control of the primary supply to the transformer is used to regulate the output, and in large pipe structures temperatures of 550° C are reached in about 1 hour. The same method has also been employed for preheating joints prior to welding. Similar processes are also carried out at frequencies of about 2 kc/s.

At frequencies in the range provided by motor-alternators one of the most important applications has been to the heating of bar stock prior to forging.[53, 54] Induction-heating equipment for forging requires less floor space than alternative equipment fired by other fuels, and the general working conditions are improved. The uniformity of heating is high, and because of the rapid heating achieved, scaling is less and consequently the die life is increased. A large steel-forging installation in this country, claimed to be the largest in Europe, has 900 kW of 10 kc/s power and 2 400 kW of 3 kc/s power provided by six 150 kW 10 kc/s generators and six 3 kc/s alternators having output powers from 250 to 800 kW. The billets are carried through channel-type heating coils on rotary hearths, and there is a high degree of mechanization throughout the plant. Other automatic induction forges are used in the manufacture of steel bolts. In one installation ten machines for ½–¾ in diameter bolts are fed from two 500 kW 10 kc/s alternators.

Induction heating using 10 kc/s alternators is also being applied to the through hardening of bar stock and to the surface hardening of components, such as camshafts and gearwheels,[53, 55] many hardening processes being carried out on automatic machines. Frequently the component is rotated in the inductor to ensure uniform heating, and electrical control of both the heating and quenching result in a high standard of uniformity of the treatment.

Induction heating using valve generators has been applied to melting, heat treatment of metals and fabrication. With few exceptions, the generators used have lower output powers than alternators. They are now commonly used for local through hardening, for surface hardening and for soldering or brazing components. Heating times are short, and this method is well suited to quantity production. It is usual to put the induction-heating machines in the production line, thus saving the handling needed if a separate heat-treatment shop is used. The process has many advantages over some of the other methods in use, such as speed, uniformity of treatment, small amount of deterioration in shape or surface condition and economy. Many cases are known where the use of induction heating for soldering and brazing has shown substantial economies.[56]

In all applications of induction heating much depends on the method of handling the material or components. Handling fixtures vary from simple hand-loaded jigs to semi-automatic machines which are specially designed to ensure maximum production rates. The conditions existing in the neighbourhood of induction-heating coils call for careful placing of some parts of the machine and care in the choice of the most suitable materials. The use of steel for parts in close proximity to the coil must be avoided, and insulating materials must frequently be used in place of metal. Although much has been published about induction-heating applications, less attention has been given to the design of work-handling equipment.[57]

(5) DIELECTRIC-HEATING PROCESSES

General surveys of the industrial uses of dielectric heating have been published elsewhere.[58, 59]

(5.1) Plastics

During the past ten years there has been a substantial increase in the use of dielectric heating in the plastics, rubber and wood industries, the earliest use being the preheating of thermosetting plastics. Dielectric ovens are being used extensively for preheating thermosetting powders prior to moulding. The largest single use of dielectric heating is for the sealing of thermoplastic sheets to make fancy goods, garments and packages,[60] and it has been estimated that more than 3 000 welding units are in use by about 600 manufacturers. Many of these generators have output powers of only a few hundred watts, but large-capacity welders have been developed for frequencies of about 20 Mc/s and output powers of 6 kW; such machines can make a weld up to 20 ft in length.

With the introduction of p.v.c. conveyor belting and its use on a large scale in place of rubber, various methods of preheating the belt components have been used. The development of a 10 Mc/s dielectric-heating equipment with an output power of 140 kW, which is capable of heating 6 ft-wide belting at speeds of up to 2 ft/min has been reported.[25]

Dielectric heating has been applied to the curing of both closed-cell and interconnecting-cell vinyl plastic foams; the method was developed in America, and is now being applied in Britain. The prepared resin and plasticizer is thoroughly mixed with an inert gas and deposited on a forming belt which carries it between plate electrodes. The expanded material is heated to about 150° C for gelling, the speed of treatment[61, 62] of 2 in-thick foam being about 18 in/min.

A further development is the shock-curing of resin-impregnated laminated materials. This novel method of curing some phenol-formaldehyde-impregnated materials arose from a search for electrical methods of indicating the extent of the curing process. In practice, if the mains voltage is applied to mouldings of this material whilst it is held under a low pressure at about 100° C, a current flows through the material; the current falls very rapidly to zero, and the mouldings are then found to be completely cured.[63, 64]

(5.2) Rubber

The use of dielectric heating in the rubber industry is less extensive than that in the plastics industry, but important developments have taken place. In general, full advantage cannot be taken of the rapid through-heating which the method offers because uneven heating might arise from small inequalities in the dispersion of the fillers. Despite this, the rate of heating which can safely be attained is many times that possible with other methods, and 'preforms' of rubber are heated in this way prior to moulding. Uncured rubber wound on metal components is also being preheated by making the metal part one of the h.f. electrodes. In most cases the preheated rubber is transferred to a press heated by conventional means for the completion of the curing or vulcanizing process.

(5.3) Wood

Dielectric heating is being used in the wood industry for the manufacture of panels and shapes and for the assembly of parts. Manufactures which depend on the curing of synthetic-resin glues are being accelerated by the use of dielectric heating. Urea-formaldehyde glues are commonly used, and for best results the moisture content of the wood should not exceed about 13%. The spread of the glue should be uniform and adequate pressure should be maintained during the curing period.[65]

Flat and curved plywood panels are made by through-heating the assembled glued veneers between sheet electrodes in a press. In other processes, where the electrodes can be placed on either side of the glue line, differential heating takes place and the glue is cured before the wood reaches the same temperature. With this method, the power absorbed in the wood can be as low as 30% of the total. This so-called 'glue-line heating' is employed in edge-glueing machines in which strips of wood are glued together into panels, and also in the assembly of furniture. The successful application of dielectric heating in wood assembly depends on the careful design and positioning of the h.f. electrodes in the jigs which clamp the components during the curing cycle.[66–71]

A large plant for the continuous production of high-quality boards made from resin-impregnated wood waste has been developed and put into production use. The impregnated wood chips are fed to a conveyor and pass between h.f. electrodes and into a continuous press, where the resin is cured by dielectric heating from three 30 kW 18 Mc/s generators.[72]

Much work has been carried out on the drying of timber by dielectric heating; results have so far been only partially successful, and limited practical use has been made of this process.[73–75]

(5.4) Miscellaneous

Other applications of dielectric heating have been tried, and although many have proved to be technically feasible, they have not yet reached wide-scale production use. Among these is the curing of foundry cores: with the introduction of synthetic-resin binders in the making of cores, the possibility of baking them quickly by using dielectric heating was explored. It was found practicable to bake cores made with either ureaformaldehyde or phenolformaldehyde glues in times of up to 5 min, and with the more recent introduction of core carriers or driers of polyester-resin-bonded materials, the few defects of the process were removed.[76] The barrier to present progress is probably one of cost, and changing conditions may well affect this.

(6) RADIANT HEATING

The largest single use of radiant heating for treatments up to about 300° C continues to be for the stoving of paint finishes on metal products, and the range of products finished in this way is now extensive. An important advantage of this method is rapid heating, and consequently comparatively small plants are required. The maximum heating effect is available within a short time of switching on the ovens, which are of low thermal capacity.

Progress has also been made in the associated field of electrostatic paint spraying with the introduction of a new method of atomizing the paint. Rotating discs and cups fed with paint are used to produce a mist of paint in place of the previous compressed-air spraying equipment, and many components which are produced in large quantities are being sprayed in mechanized plants by this method.[77]

Within the past few years, radiant heating has been used to accelerate the drying or curing of both cellulose and synthetic finishes on wood.[78] Furniture, cabinets and structural panels are finished in this way in largely mechanized plants. The advantages of using radiant heat arise from the saving in processing time which it permits: in a 5-stage finishing process using cellulose finishes, an air drying time exceeding 18 hours can be reduced to less than 3 hours.

Many existing fillers, sealers and lacquers are suitable without modification for force drying, but unless the proper procedure is followed, blistering of the finish can occur; it is avoided by careful filling and by control of film thickness and rate of heating. Stoved synthetic finishes are produced in a similar way, and have greater toughness and resistance to heat and solvents than cellulose finishes.

In the plastics field, radiant heating is being used for softening thermoplastic sheets prior to forming and moulding and also for the gelling of p.v.c. pastes. Sheets of vinyl-resin-based materials, polythene and many others are heated by radiant panels, elements or lamps to the softening temperature prior to being formed, usually on metal moulds under atmospheric pressure. This process is used both for parts which are made in large quantities, such as some lighting fittings, and also for smaller quantities of more specialized components.[79]

In the manufacture of p.v.c.-coated fabrics, paste is applied to the cloth either by knife or roller and the material is then heated by radiation to 150–200° C for fusion to take place. Plain and embossed coated cloths are made in this way in a variety of colours, and one of the advantages of using the sheathed-wire-element radiant plant is that the rate of heating does not vary much with different colours.[62]

The drying of some materials has also been carried out by radiant heating, but, as with other electrical methods, radiant heating is not commonly used for drying materials in bulk.[80]

In the textile field, radiant heating is being used for the stabilization treatment of some woven synthetic-fibre materials. The fabric, stretched on a stenter, is passed through a radiant-heating oven to raise its temperature to near the melting point. This treatment ensures that subsequent handling and processing of the material does not give rise to dimensional changes.

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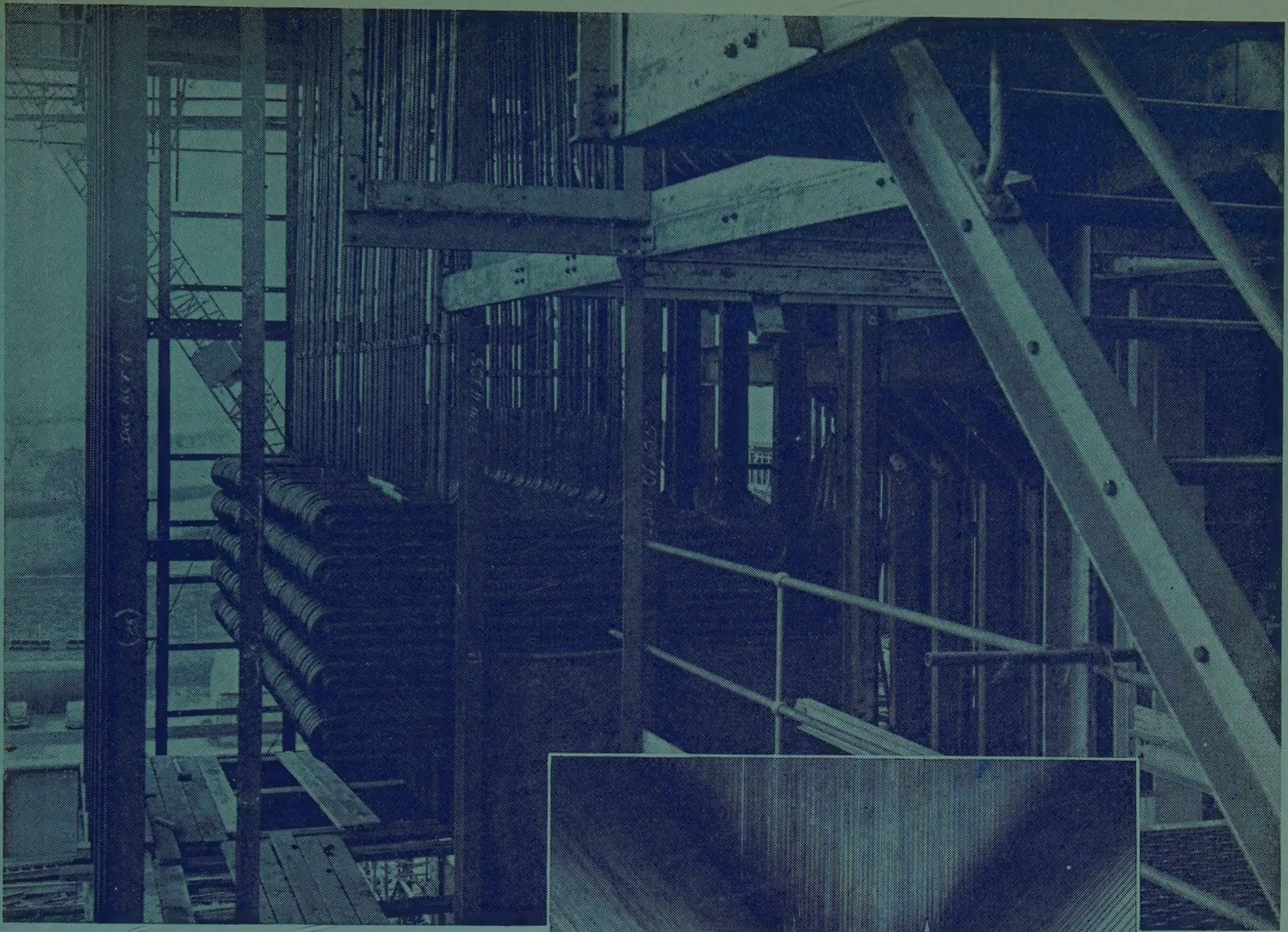
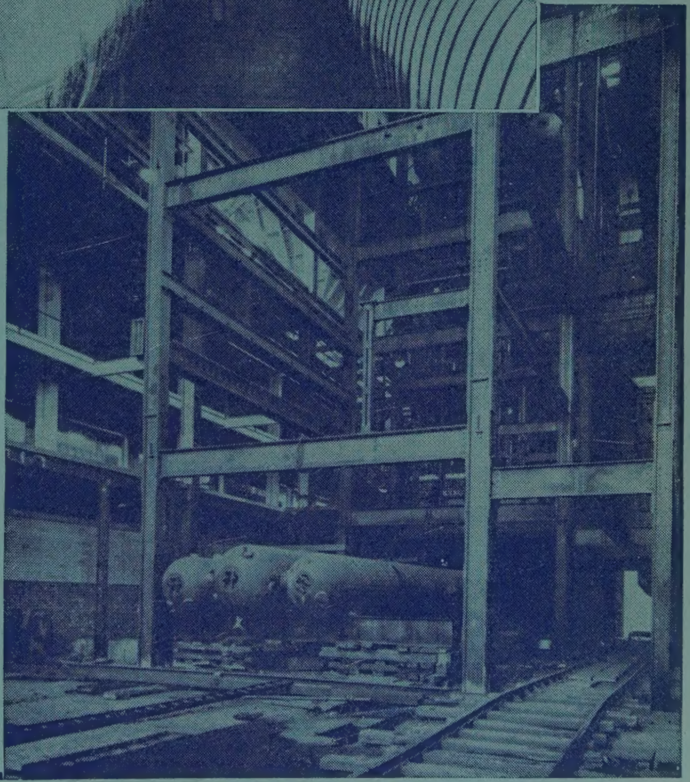


Views of typical boiler installations.



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Example.—SMITH, J.: 'Overhead Transmission Systems', *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 (102 A, p. 1234).

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